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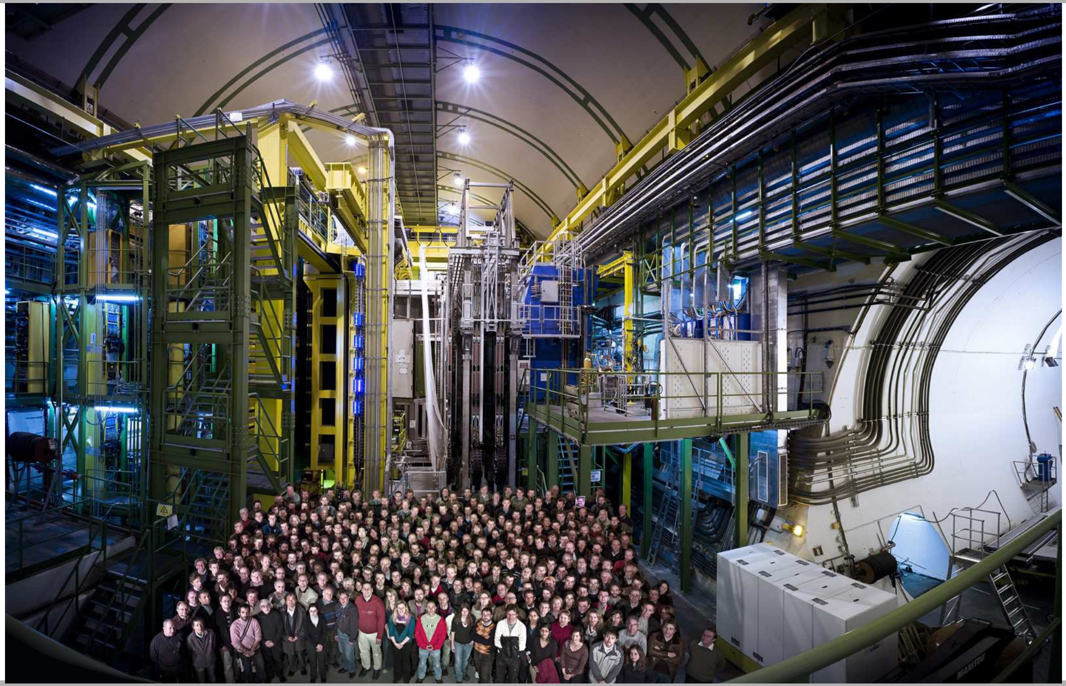
Exotic meson spectroscopy at LHCb

M. Kreps

Physics Department



Introduction

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- In the quark model we think of hadrons as $q\bar{q}$ or qqq
- But there is nothing preventing other combinations

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

→ Where are all those combinations with more than 3 quarks or anti-quarks?

Introduction - molecules

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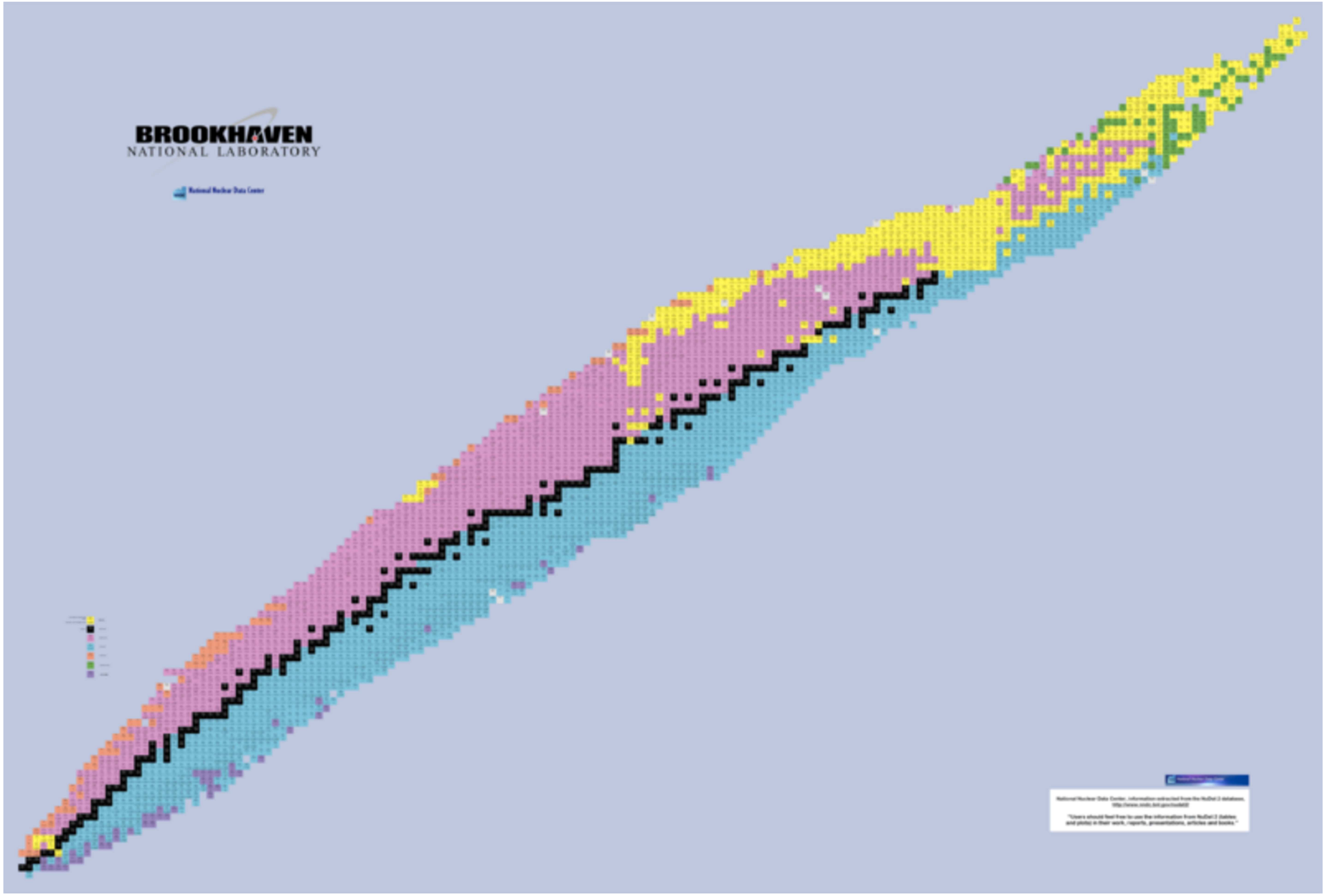

- There are lot of objects composed of baryons

Introduction - molecules

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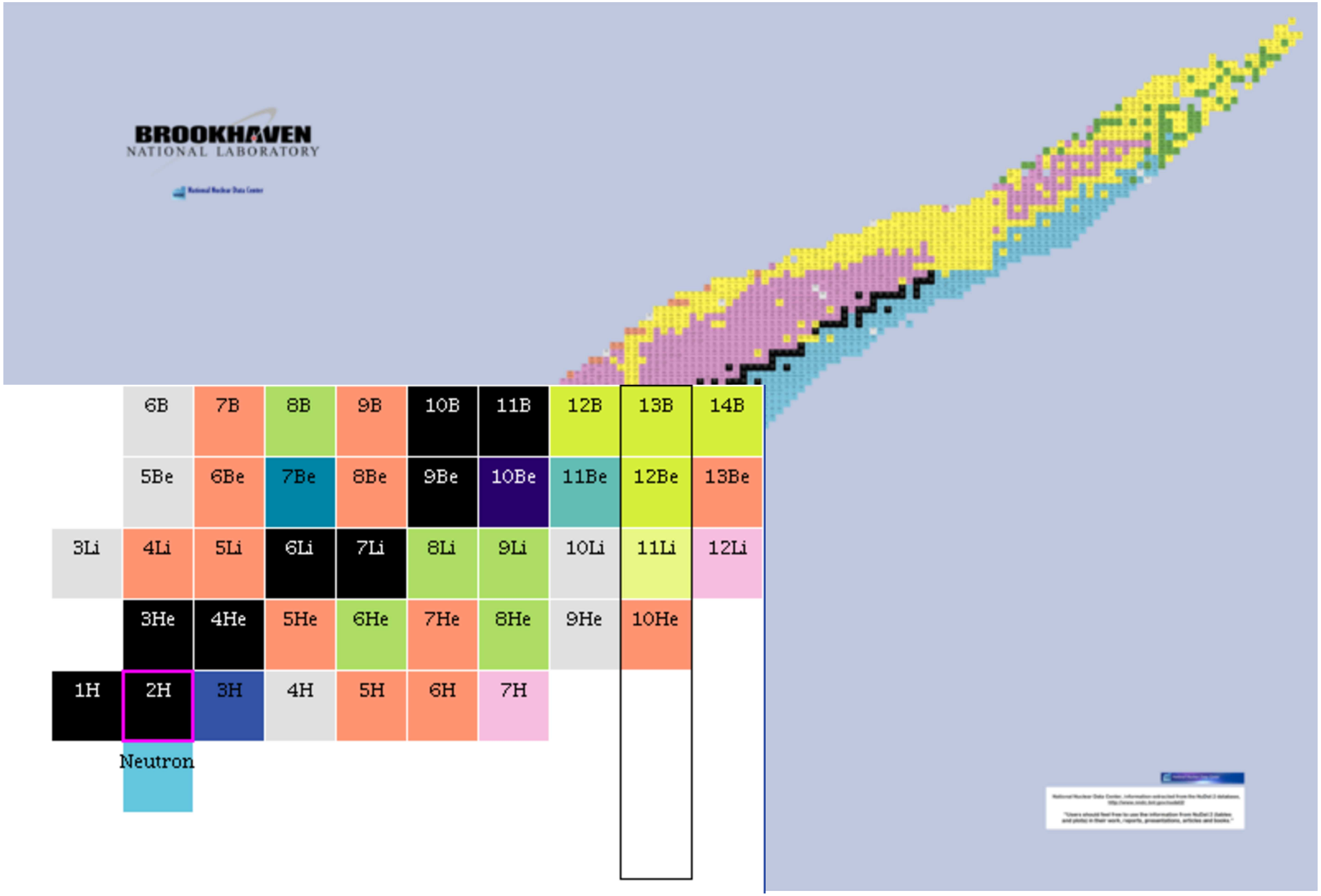

- There are lot of objects composed of baryons
- Where are similar objects from mesons?

Scalar mesons

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NOTE ON SCALAR MESONS BELOW 2 GEV

Revised September 2013 by C. Amsler (Univ of Bern), S. Eidelman (Budker Institute of Nuclear Physics, Novosibirsk), T. Gutsche (University of Tübingen), C. Hanhart (Forschungszentrum Jülich), S. Spanier (University of Tennessee), and N.A. Törnqvist (University of Helsinki).

V. Interpretation of the scalars below 1 GeV: In the literature, many suggestions are discussed, such as conventional $q\bar{q}$ mesons, $q\bar{q}q\bar{q}$ or meson-meson bound states. In addition one expects a scalar glueball in this mass range. In reality, there can be superpositions of these components, and one often depends on models to determine the dominant one. Although we have seen progress in recent years, this question remains open. Here, we mention some of the present conclusions.

The $f_0(980)$ and $a_0(980)$ are often interpreted as multiquark states [140–144] or $K\bar{K}$ bound states [145]. The insight into

From RPP by PDG

- Candidates beyond $q\bar{q}$ mesons exist, but real trouble is how to decide whether they are $q\bar{q}$ or something else

Charmonium

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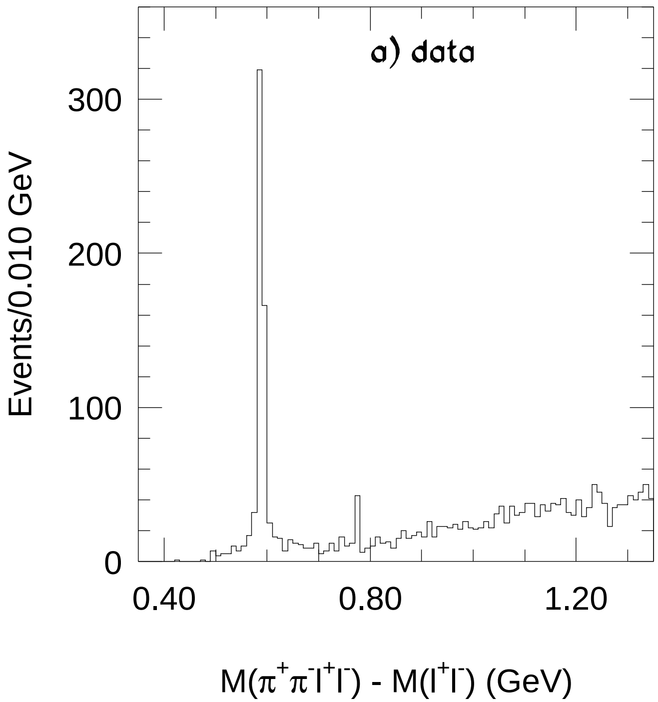
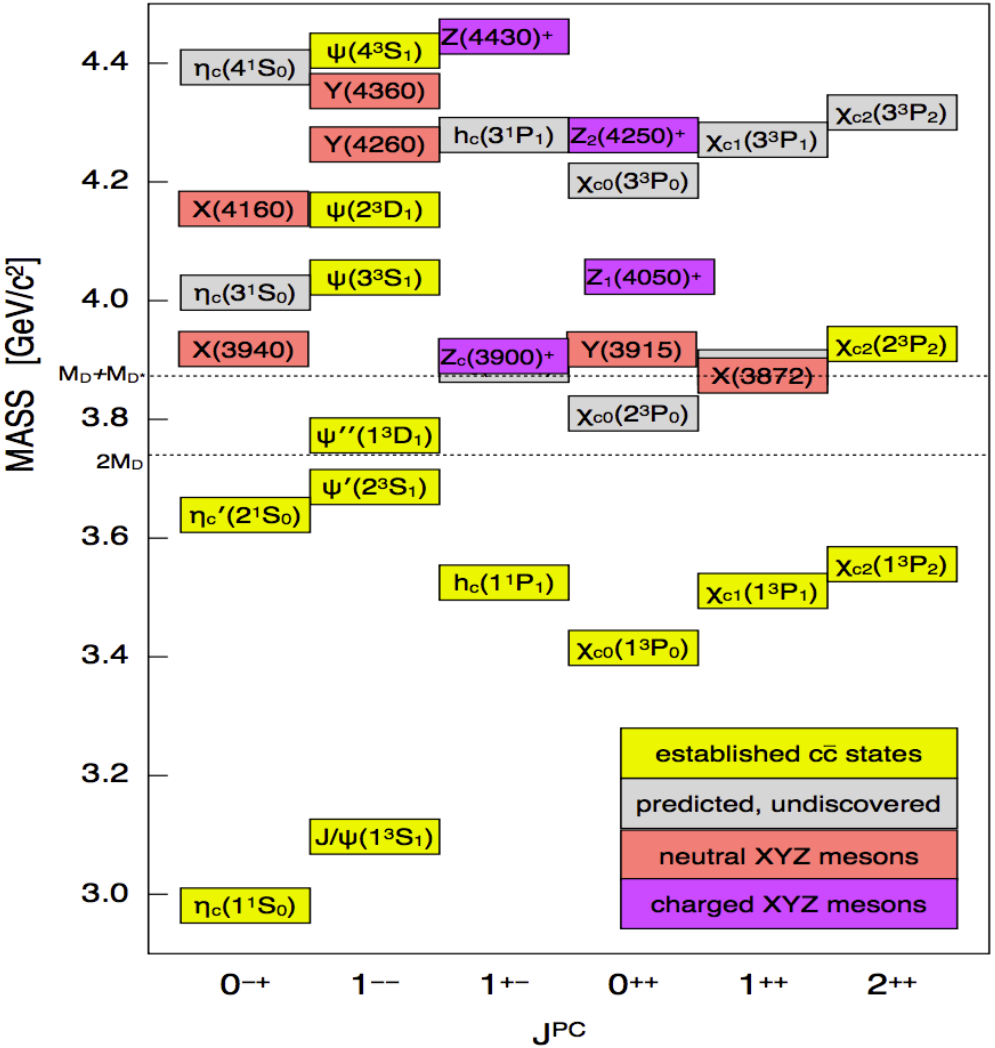
- Back in 2003, many expected states still missing
- Belle started to search for them and quickly found one
- Did not fit into expected spectra

- Mass close to $m(D^0) + m(D^{*0})$

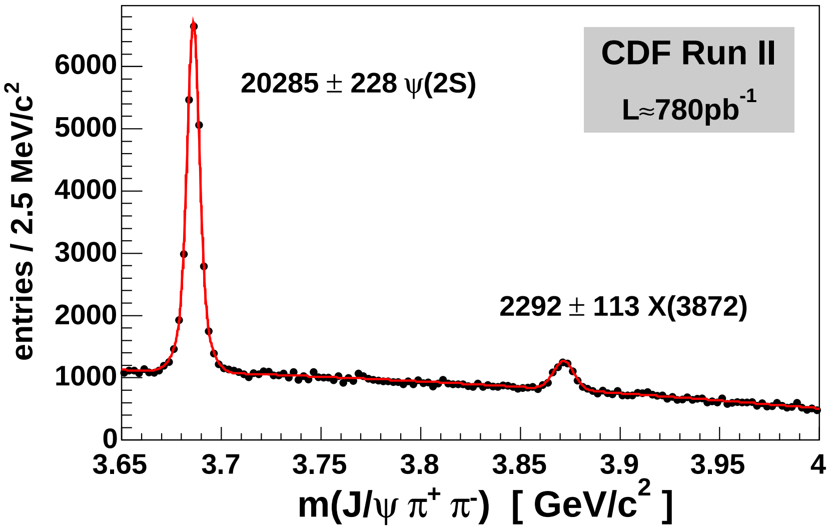
PRL 91, 262001

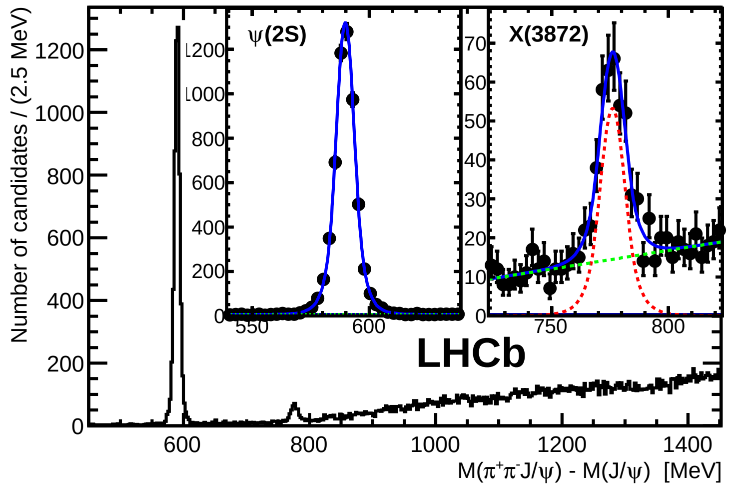


arXiv:1403.1254



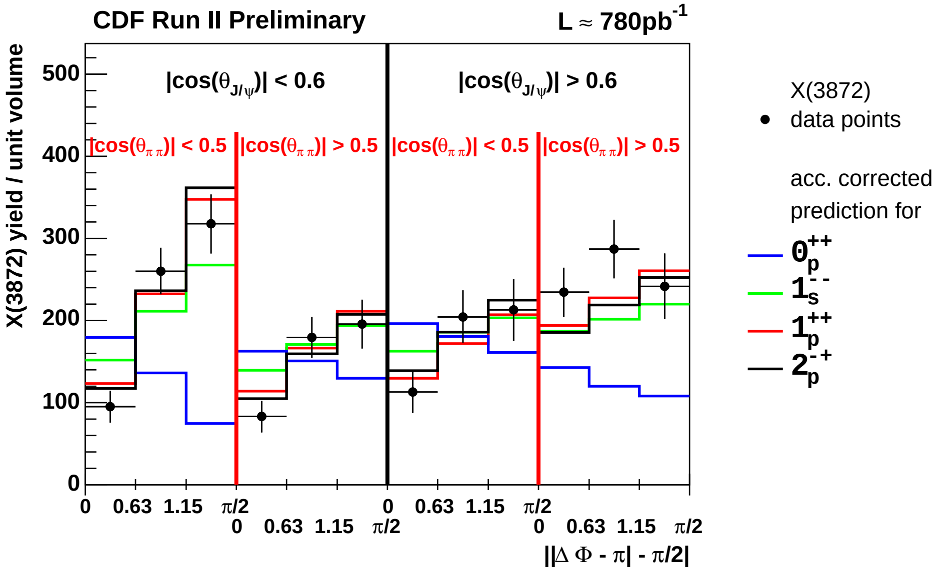
$X(3872)$ properties

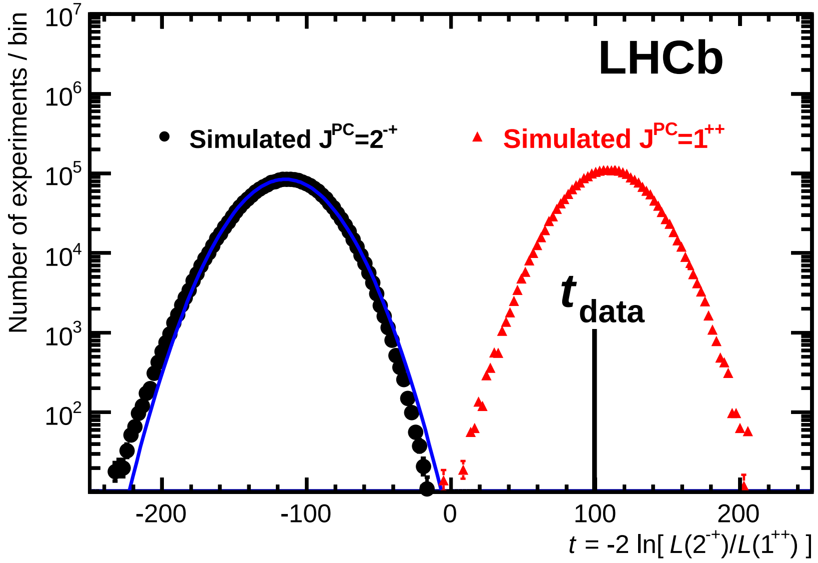




PRL 110, 222001

PRL 98, 132002





- Quantum numbers $J^{PC} = 1^{++}$

What is $\mathrm{X}(3872)$?

- Lot has been done for $X(3872)$
- Despite all effort during 10 years, our understanding of what $X(3872)$ is still about same
- To find convincing case of non-conventional meson is hard

$Z(4430)^+$ history

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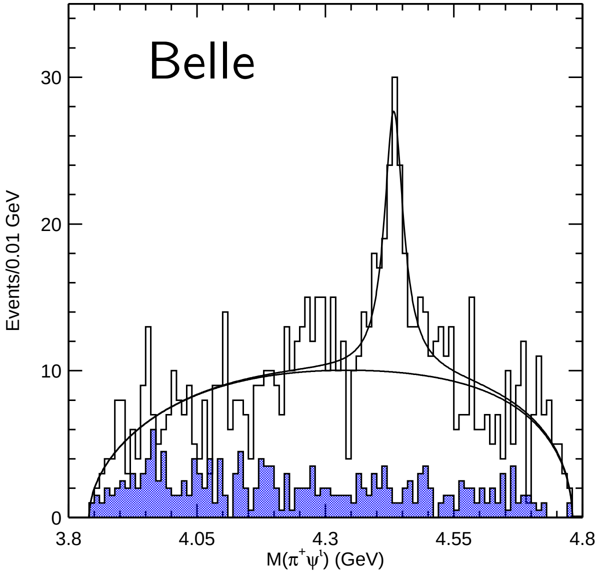
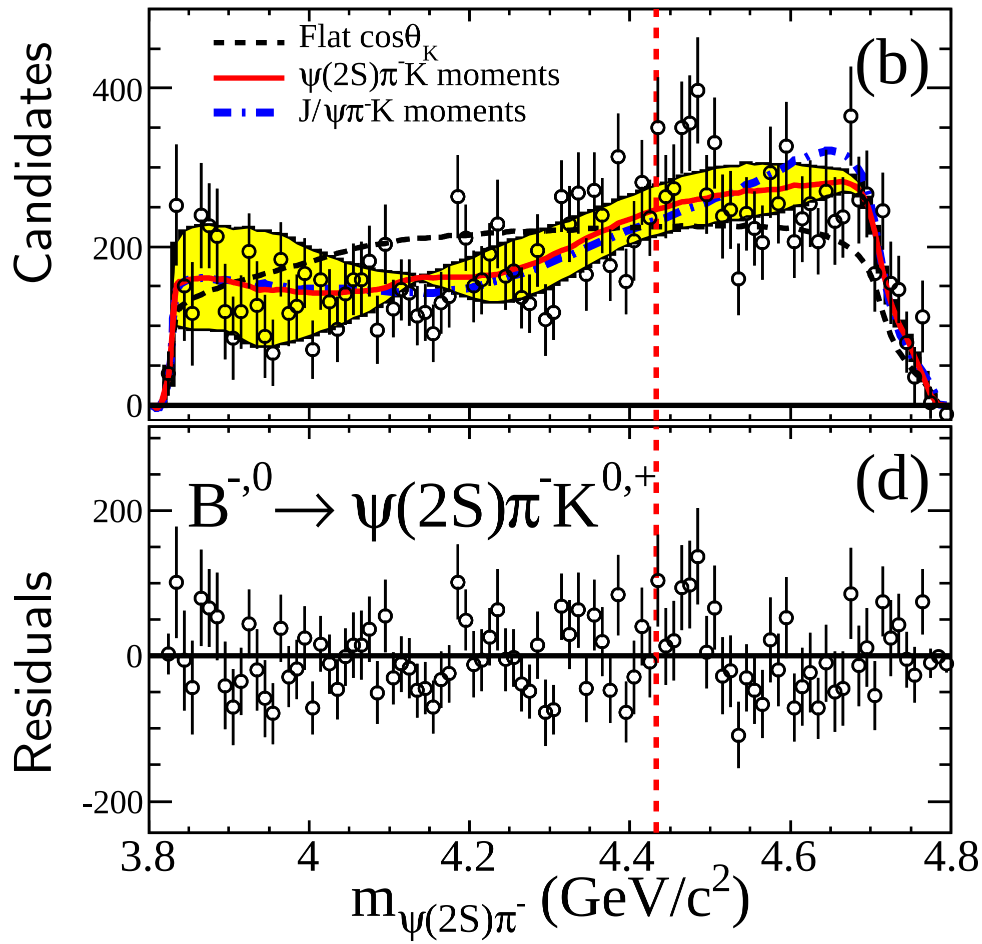
PRL 100, 142001





PRD 79, 112001

- Seen by Belle, but not Babar
- Data consistent
- Charged state

$\rightarrow$ Cannot be $c\bar{c}$

- Latest Belle result uses 4D analysis
- Is it real and if yes, is it resonance?

$\mathbf{Z(4430)^+}$ history

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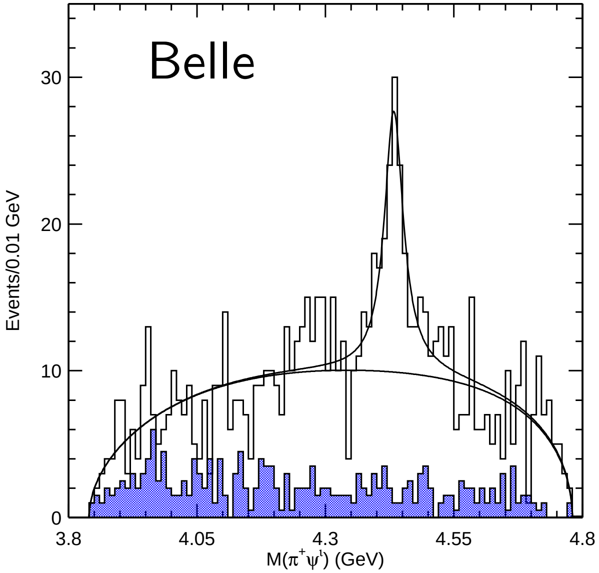
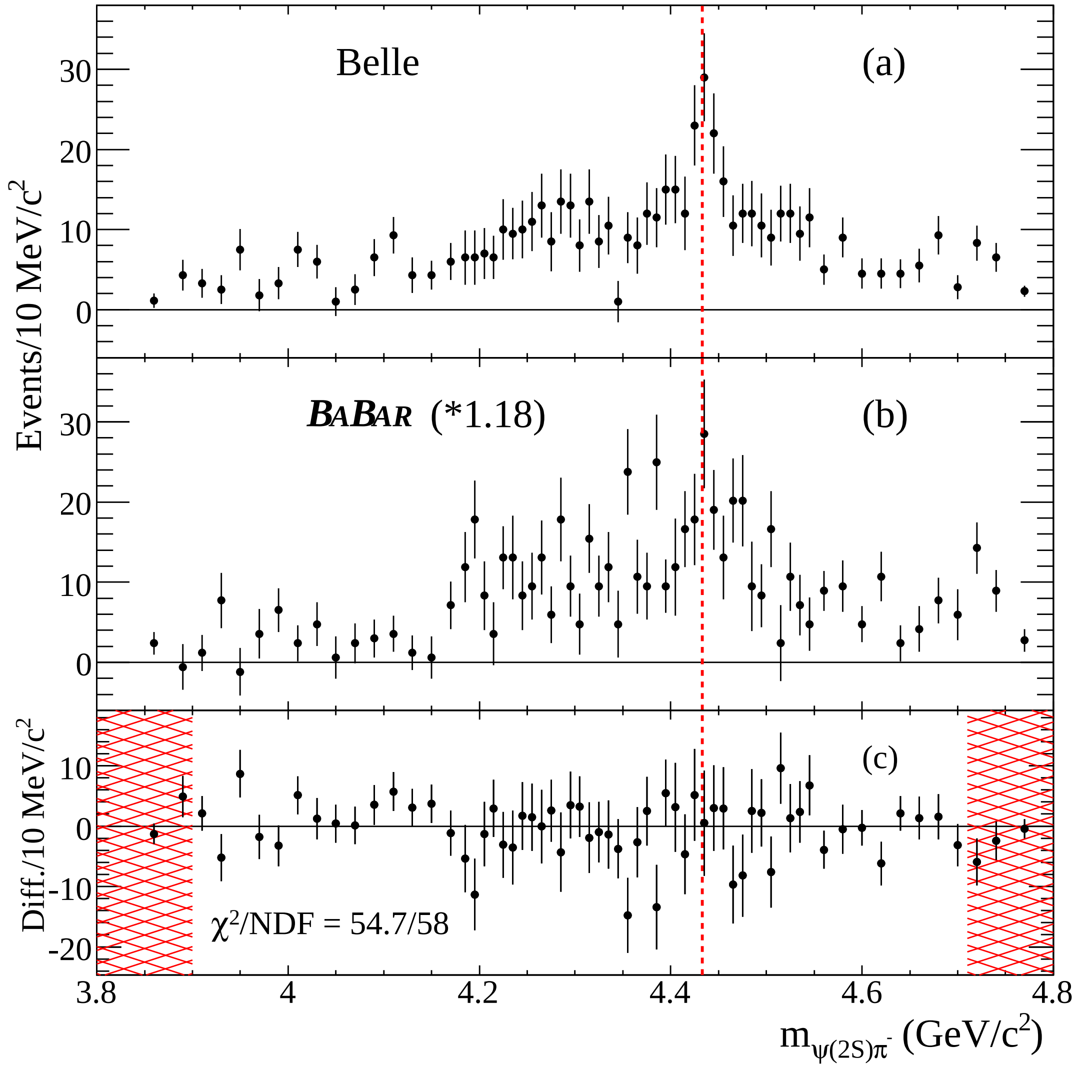
PRL 100, 142001





PRD 79, 112001

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- $\rightarrow$ Cannot be $c\bar{c}$
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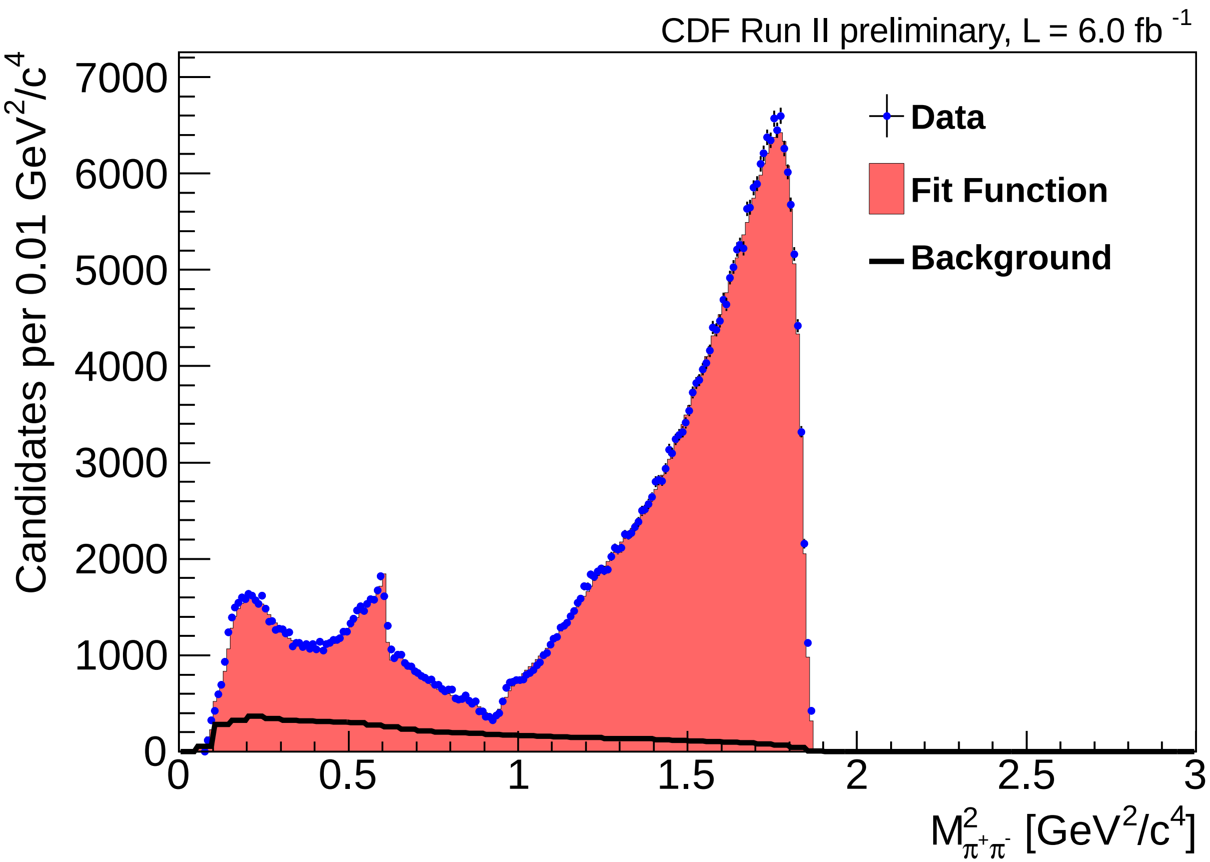
- Is it real and if yes, is it resonance?

Issue of reflections

- Look to bit simpler system of $D^0 \to K_S\pi^+\pi^-$ (only 2D rather than 4D system)
- Inspecting $\pi^+\pi^-$ invariant mass, is there state around 1.8 GeV?



PRD 86, 032007 (2012)

Issue of reflections

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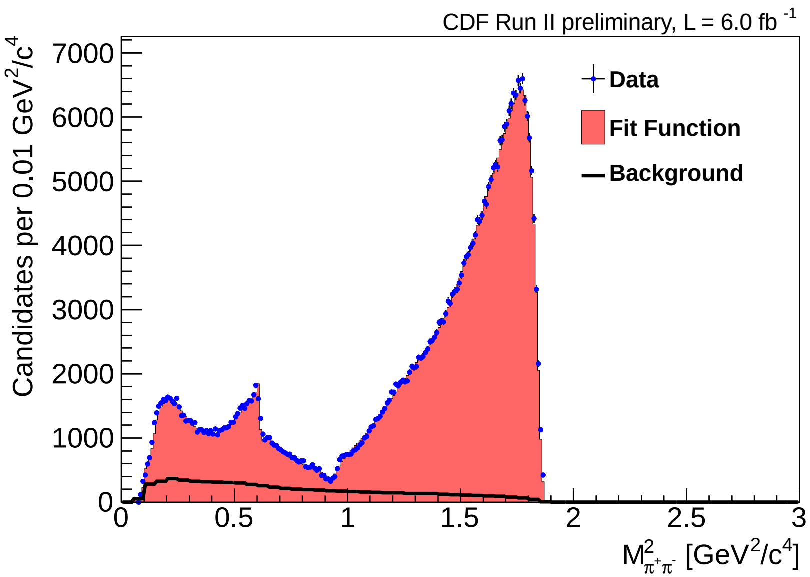
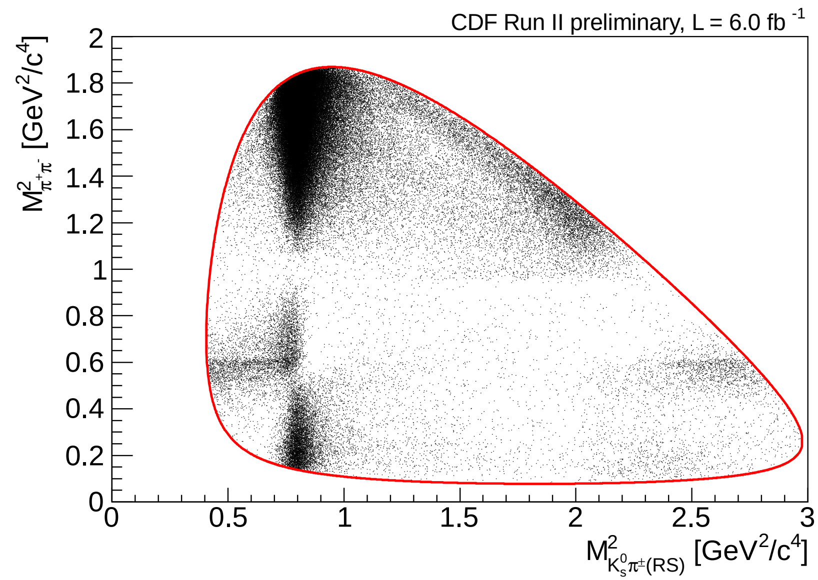
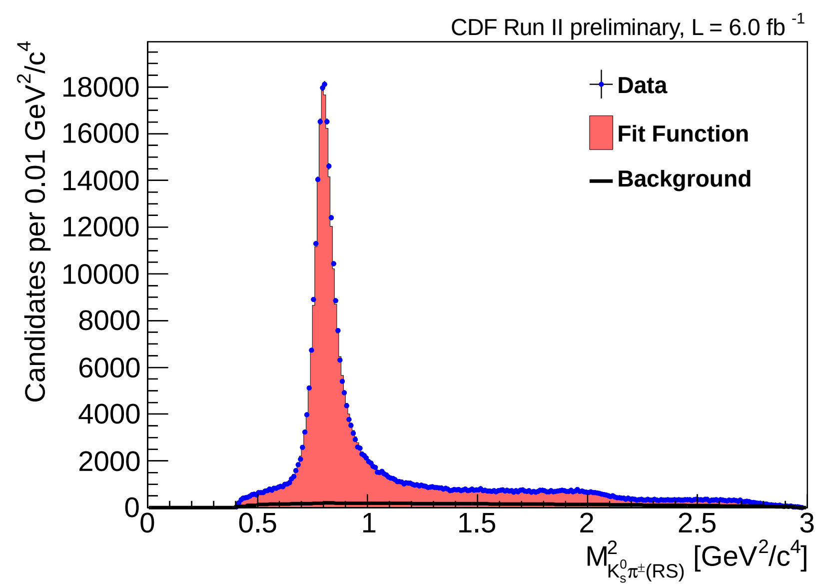




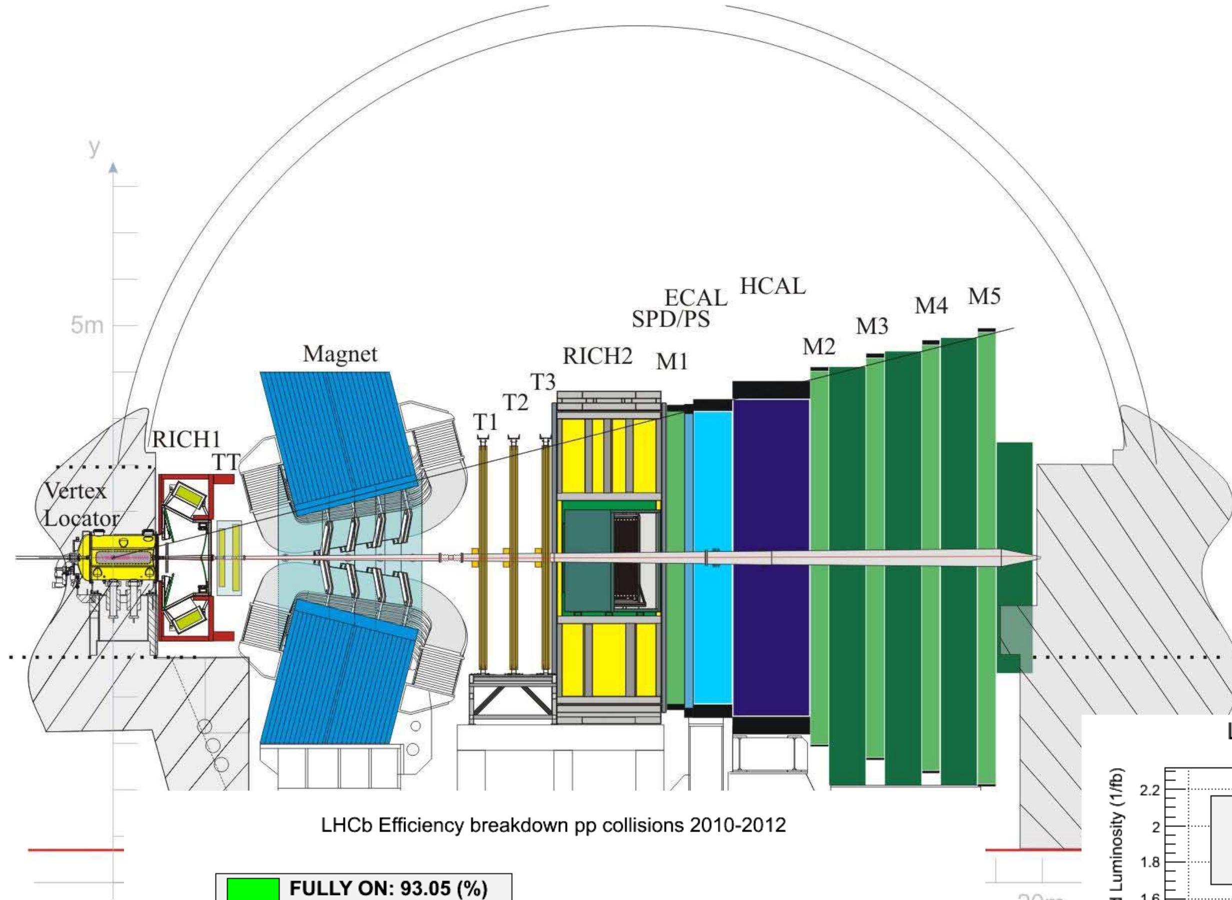
PRD 86, 032007 (2012)

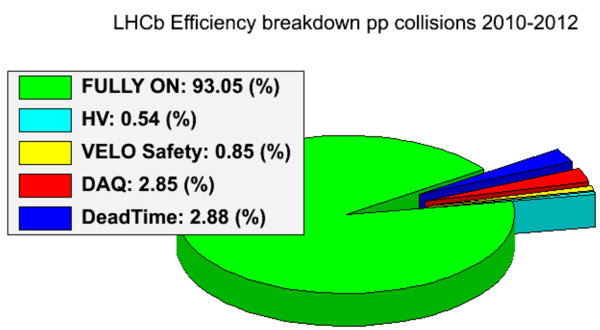
- No new $\pi^+\pi^-$ resonance
- What is seen in $\pi^+\pi^-$ is result of reflection from $K_S\pi$ and its angular structure
- Need to be careful when making claims in this type of systems

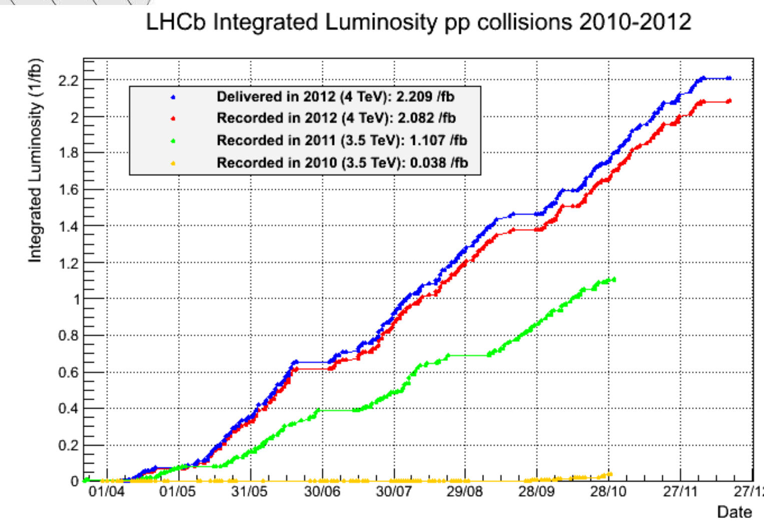


LHCb detector

- Good mass resolution
- Good time resolution
- High trigger rate on c and b
- Uniform running conditions







LHCb detector

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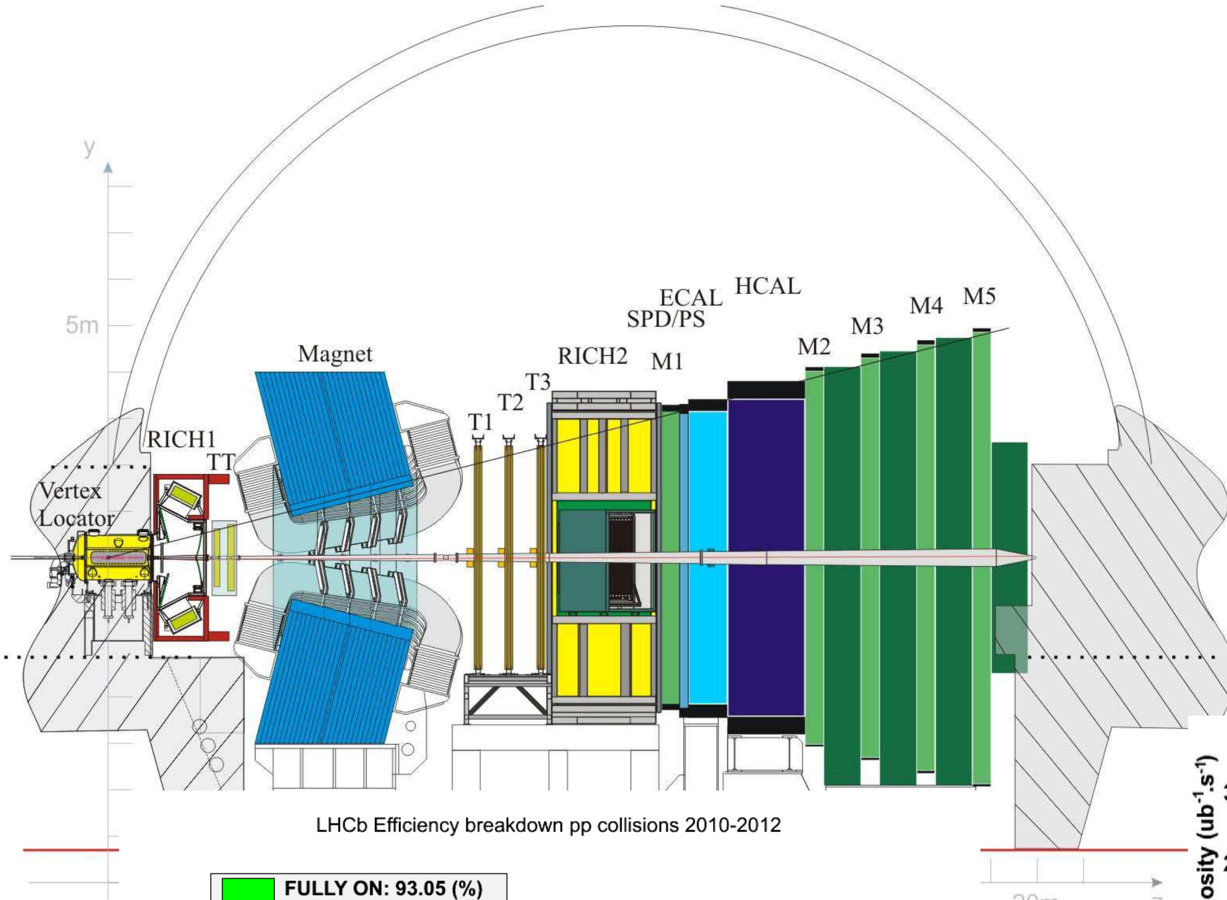

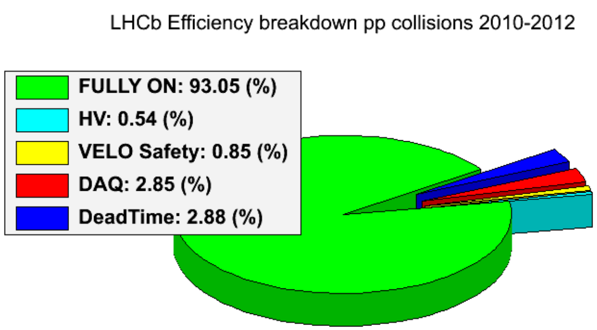

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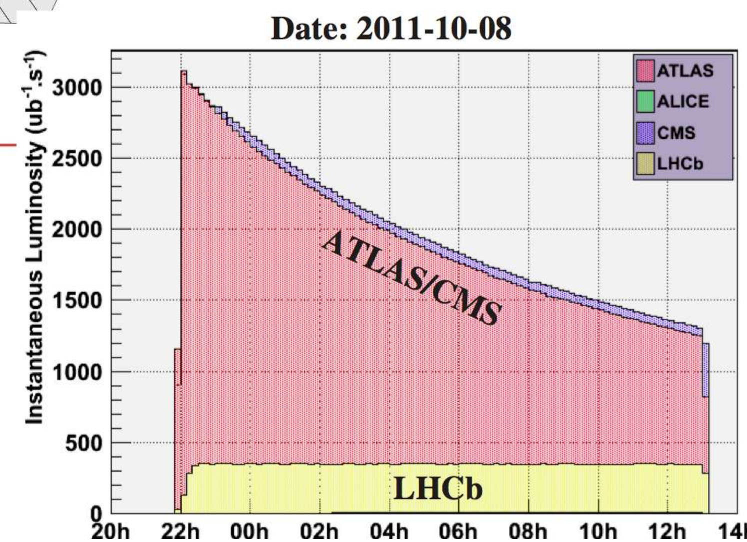
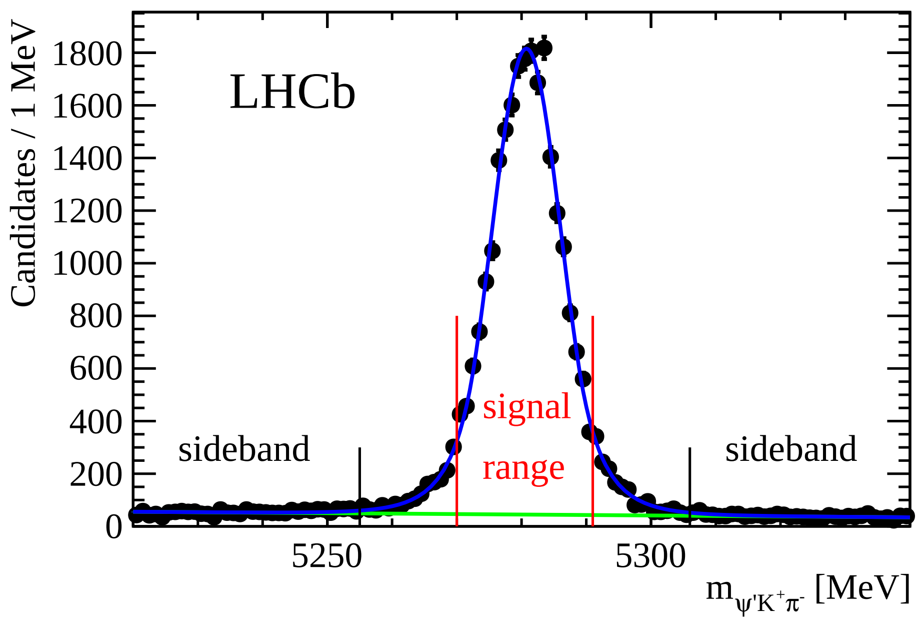


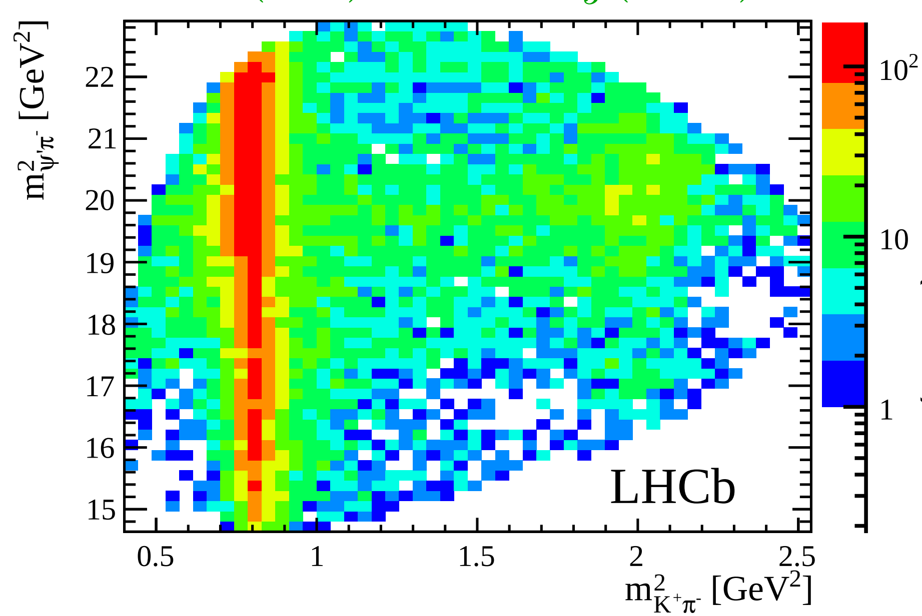
Data sample

- Use $B^0 \to \psi(2S)K\pi$ decays
- Large statistics (> 25k), about 10 times what B-factories had
- Very clean signal, background $4\,\%$ of events (about 8% at B-factories)
- Perform both model-independent analysis (BABAR) and amplitude fit (Belle)



Only 2 out of 4 dimensions

$K^*(892)$ $K_J^*(1430)$



PRL 112 (2014) 222002

Amplitude analysis

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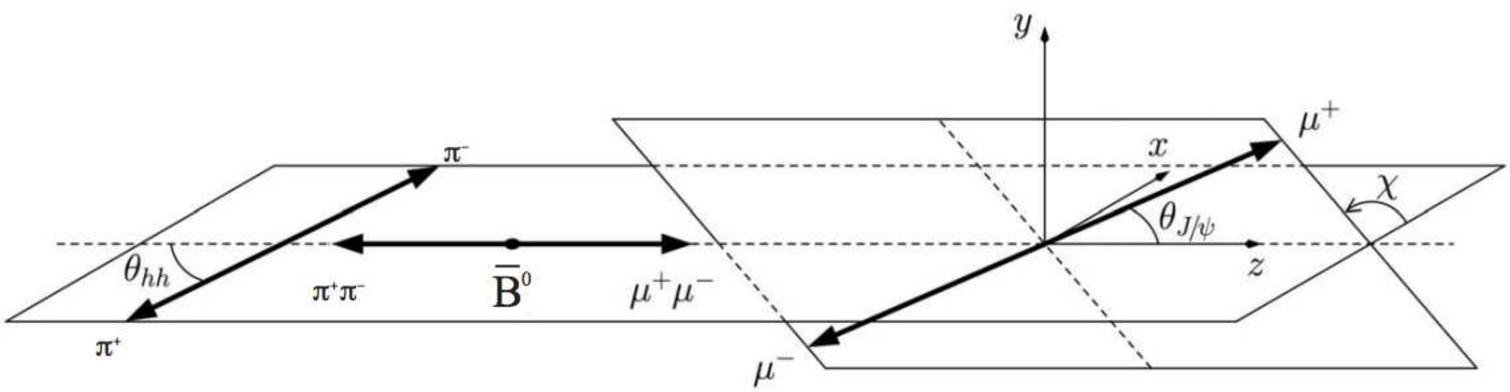

- Full 4D amplitude analysis
- Amplitude

Rotation between helicity frames

$$|M|^2 = \sum_{\Delta\lambda_\mu} \left| \sum_{\lambda_\psi} \sum_k A_{k,\lambda_\psi}(\Omega|m_{0k}, \Gamma_{0k}) + \sum_{\lambda_\psi^Z} A_{Z,\lambda_\psi^Z}(\Omega^Z|m_{0Z}, \Gamma_{0Z}) e^{i\Delta_\mu \alpha} \right|^2$$

- Mass described by relativistic Breit-Wigner
- Angular part using helicity formalism
- Imposes model how invariant mass distribution should look like

Amplitude analysis

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$$|M|^2 = \sum_{\Delta\lambda_\mu} \left| \sum_{\lambda_\psi} \sum_{k} A_{k,\lambda_\psi}(\Omega|m_{0k}, \Gamma_{0k}) + \sum_{\lambda_\psi^Z} A_{Z,\lambda_\psi^Z}(\Omega^Z|m_{0Z}, \Gamma_{0Z}) e^{i\Delta_\mu \alpha} \right|^2$$

$$A_{k,\lambda_\psi}(\Omega|m_R, \Gamma_R) = F_B^{L_B} \left(\frac{p_B}{m_B}\right)^{L_B} R(m|m_R, \Gamma_R) F_R^{L_R} \left(\frac{p_R}{m_R}\right)^{L_R} Z(\Omega)$$

Blatt-Weisskopf form factor

Orbital momentum part

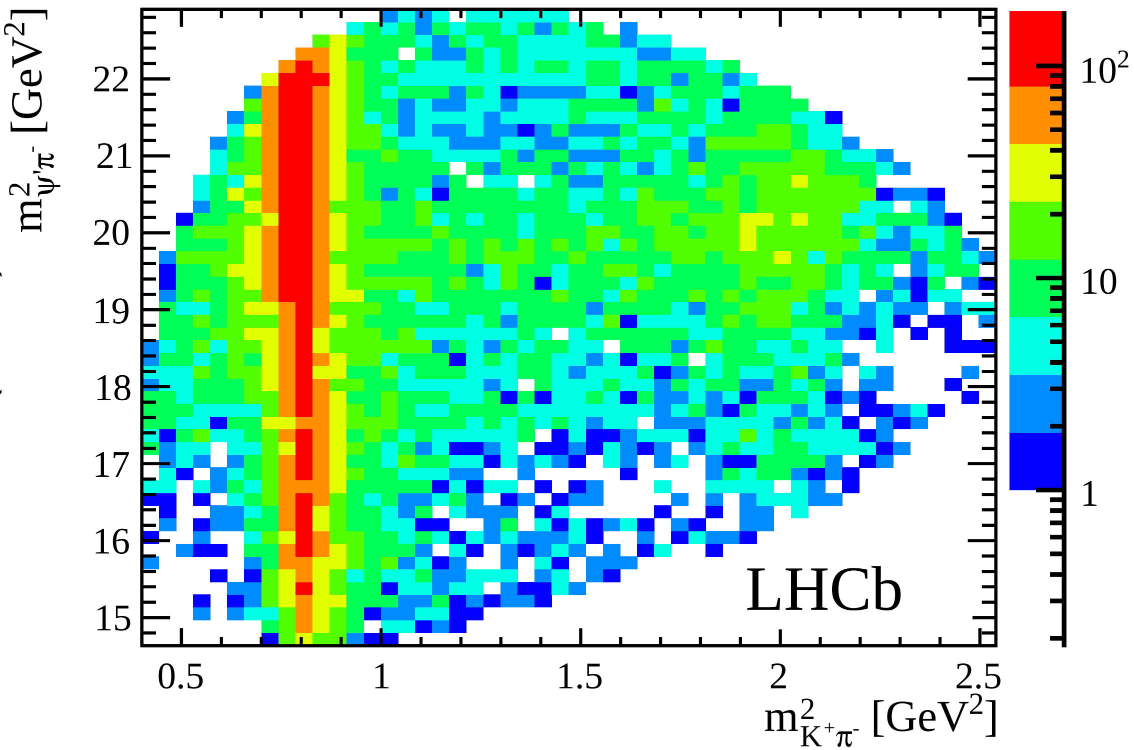
Angular distribution (Helicity)

$$R(m|m_R, \Gamma_R) = \frac{1}{m_R^2 - m^2 - i m_R \Gamma(m, \Gamma_R)}$$

$$\Gamma(m, \Gamma_R) = \Gamma_R \left(\frac{p_R}{p_{R0}}\right)^{2L_R+1} \frac{m_R}{m} F_R^2$$

Model independent method

PRL 112 (2014) 222002



- Test whether contributions in $K\pi$ system can describe data
- Do not impose specific model for resonances

$\rightarrow$ Model independent test

- Try to build up model which has proper behaviour for $K\pi$ resonances
- But avoid imposing assumptions on the shape of $m(K\pi)$ for resonances
- Construct Dalitz plot for pure $K\pi$ activity and project on $\psi(2S)\pi$ axis

- See whether model and data agree

Model independent method

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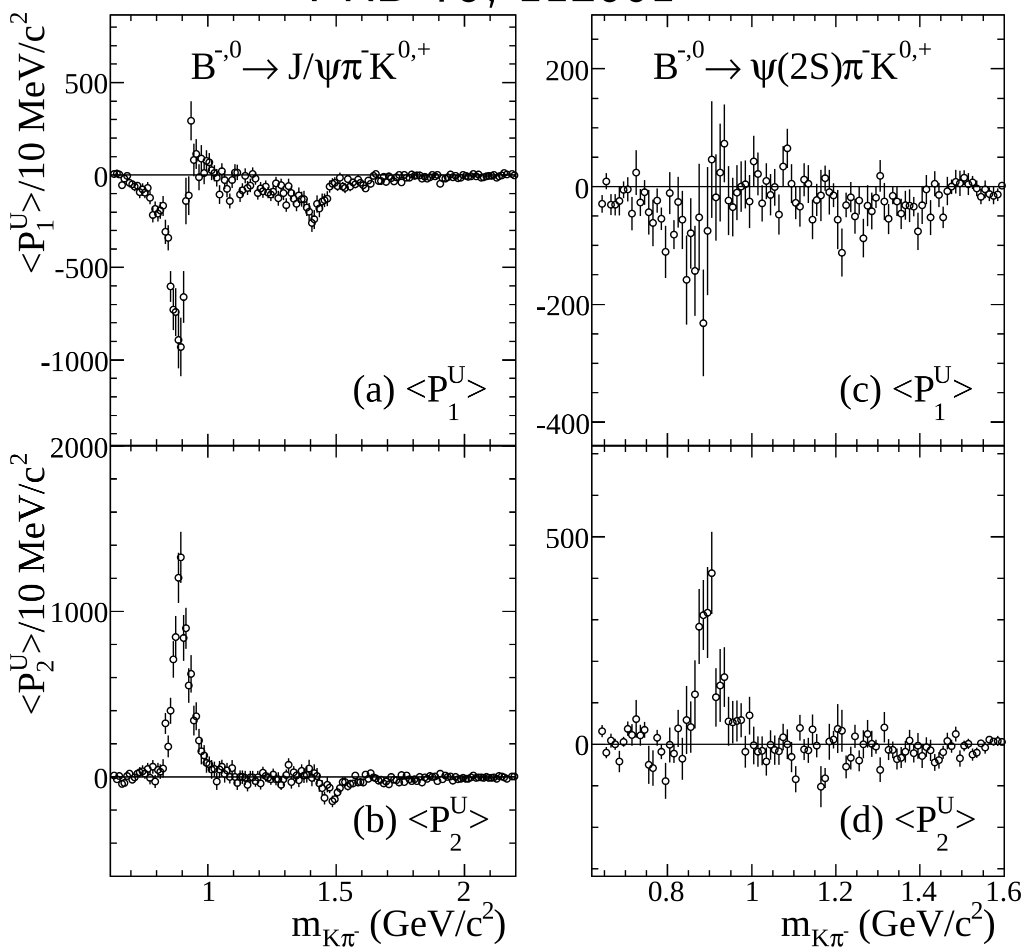
PRD 79, 112001



- Look to $\cos(\theta_K)$ in bins of $K\pi$ mass
- Allows to find out which spins contribute

$$\sum_i \frac{1}{\epsilon_i} P_l(\cos\theta_{Ki})$$

- Take only moments corresponding to $J \leq 2$
- Construct Dalitz plot and project on $\psi(2S)\pi$ axis

Why Legendre moments?

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$$
\begin{aligned}
\langle P_1^U \rangle &= \boldsymbol{S_0 P_0 \cos(\delta_{S_0} - \delta_{P_0})} + \boldsymbol{2\sqrt{\frac{2}{5}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0})} \\
&+ \sqrt{\frac{6}{5}}[P_{+1} D_{+1} \cos(\delta_{P_{+1}} - \delta_{D_{+1}}) + P_{-1} D_{-1} \cos(\delta_{P_{-1}} - \delta_{D_{-1}})]
\end{aligned}
$$

$$
\begin{aligned}
\langle P_2^U \rangle &= \boldsymbol{\sqrt{\frac{2}{5}} P_0^2 + \frac{\sqrt{10}}{7} D_0^2} + \boldsymbol{\sqrt{2} S_0 D_0 \cos(\delta_{S_0} - \delta_{D_0})} \\
&- \left(\frac{1}{\sqrt{10}} \left(P_{+1}^2 + P_{-1}^2\right) + \frac{5\sqrt{10}}{28} \left(D_{+1}^2 + D_{-1}^2\right) \right)
\end{aligned}
$$

$$
\begin{aligned}
\langle P_3^U \rangle &= \boldsymbol{3\sqrt{\frac{6}{35}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0})} - 3\sqrt{\frac{2}{35}} (P_{+1} D_{+1} \cos(\delta_{P_{+1}} - \delta_{D_{+1}}) \\
&+ P_{-1} D_{-1} \cos(\delta_{P_{-1}} - \delta_{D_{-1}}))
\end{aligned}
$$

Why Legendre moments?

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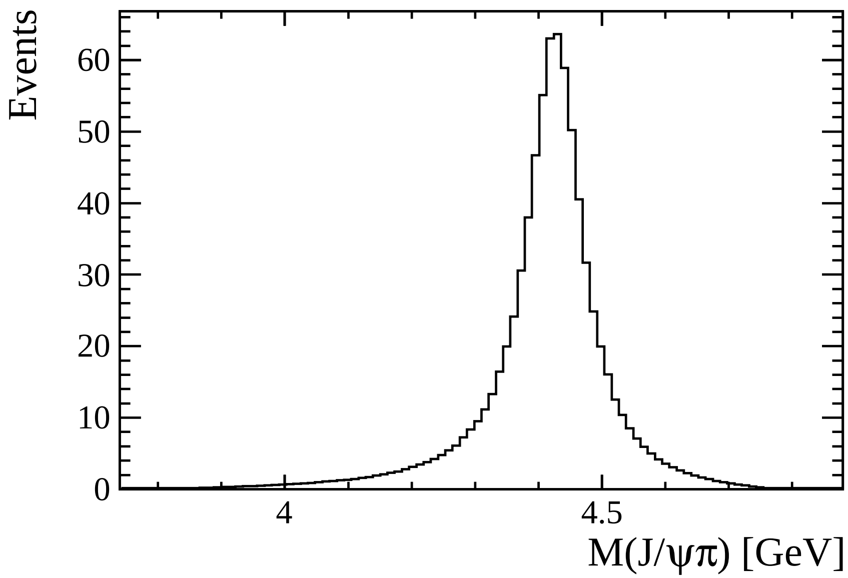
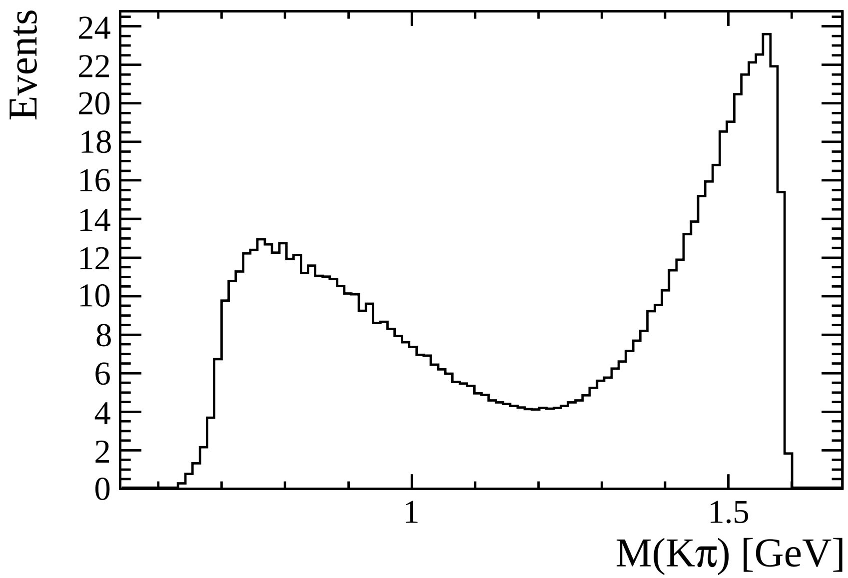
$$\langle P_1^U \rangle = \boldsymbol{S_0 P_0 \cos(\delta_{S_0} - \delta_{P_0}) + 2\sqrt{\frac{2}{5}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0})}$$
$$+ \sqrt{\frac{6}{5}} [P_{+1} D_{+1} \cos(\delta_{P_{+1}} - \delta_{D_{+1}}) + P_{-1} D_{-1} \cos(\delta_{P_{-1}} - \delta_{D_{-1}})]$$

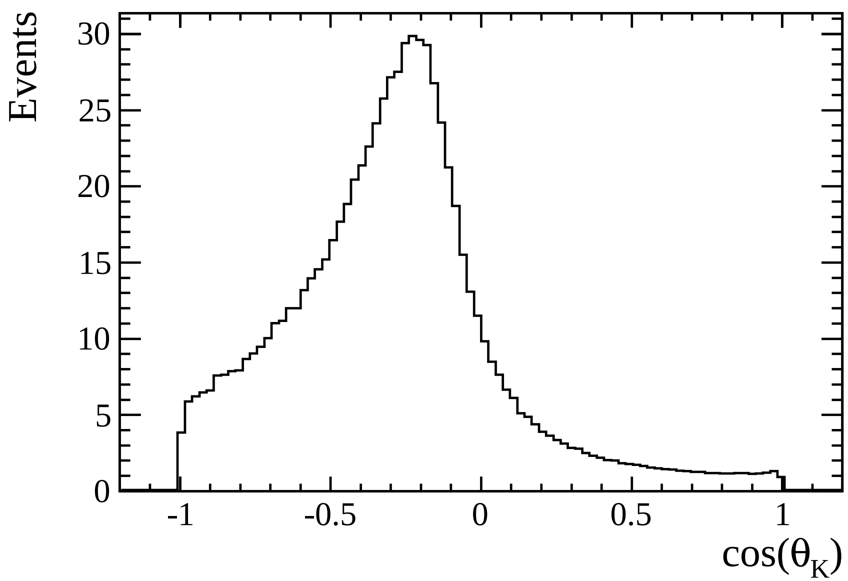
$$\langle P_2^U \rangle = \boldsymbol{\sqrt{\frac{2}{5}} P_0^2 + \frac{\sqrt{10}}{7} D_0^2 + \sqrt{2} S_0 D_0 \cos(\delta_{S_0} - \delta_{D_0})}$$
$$- \left(\frac{1}{\sqrt{10}} \left(P_{+1}^2 + P_{-1}^2\right) + \frac{5\sqrt{10}}{28} \left(D_{+1}^2 + D_{-1}^2\right) \right)$$

- Allows to cut expansion in physically meaningful way
- If we cut expansion, we select maximal spin which can contribute
- You might wonder why this is important

$\psi'\pi$ reflection



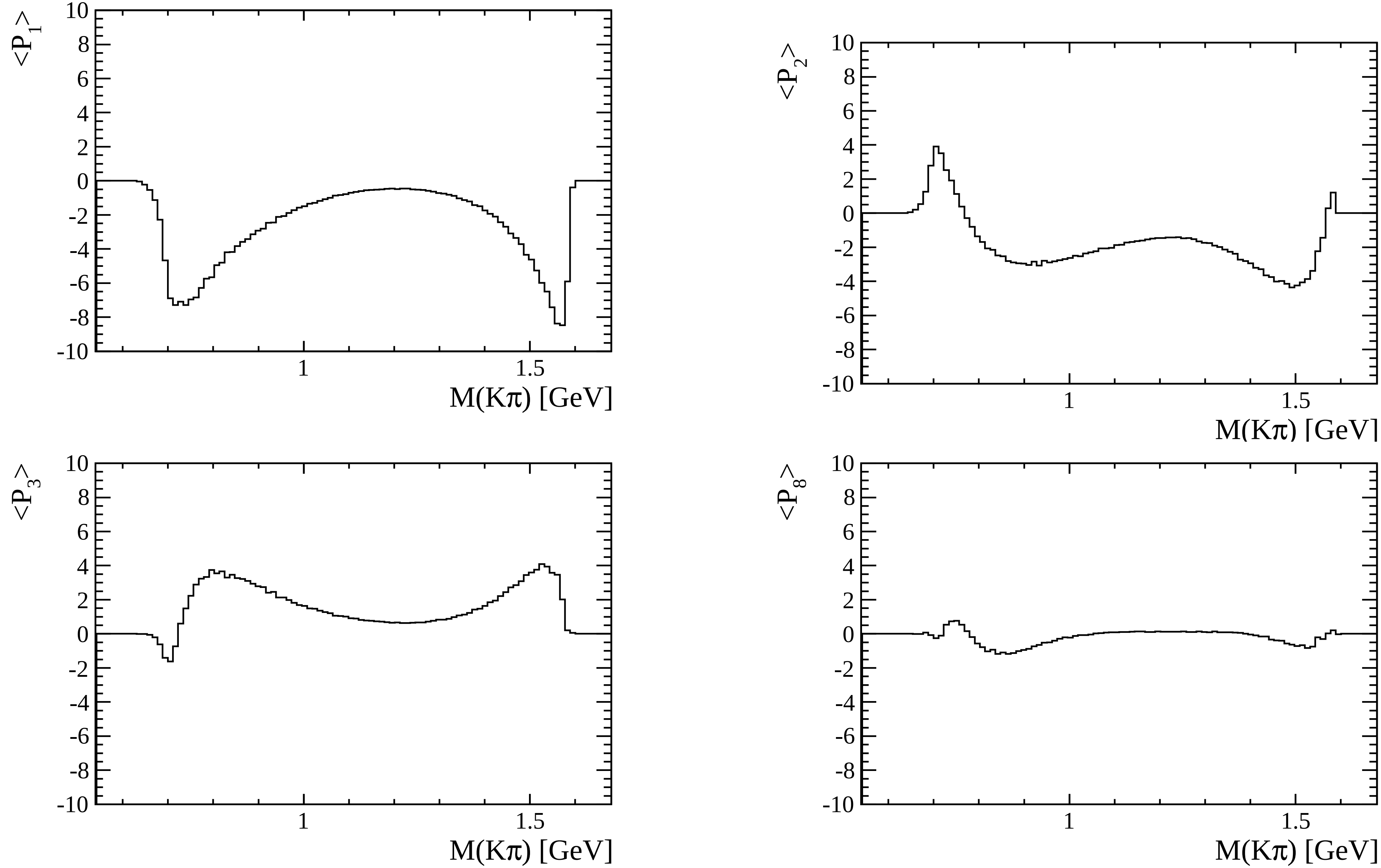




- Example of $B^0 \to Z^+(\to \psi'\pi^+)K^-$
- Such contribution reflect to whole $K\pi$ mass range
- Helicity angle distribution peaking

$\rightarrow$ Moments will receive contributions from reflection

$\psi\pi$ reflection



- Reflections make model independent method hard for measurement

Model independent result

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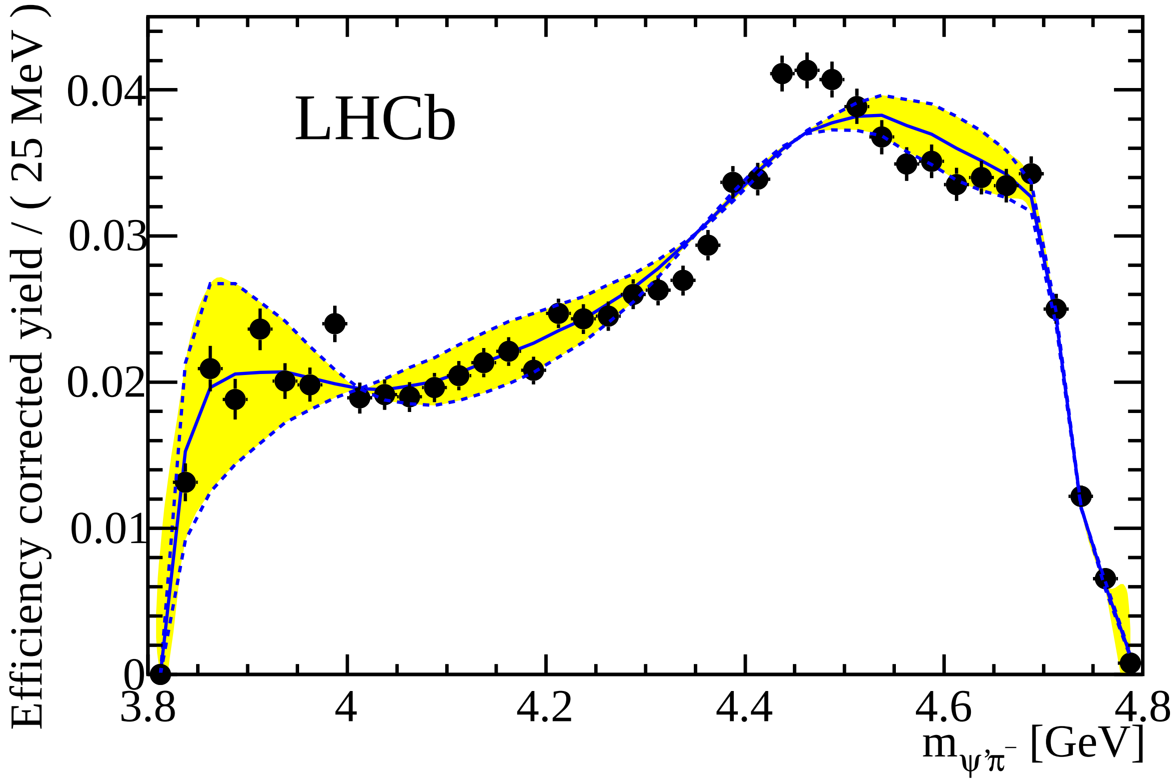

PRL 112 (2014) 222002

- Clearly, pure kaon resonances cannot explain $M(\psi(2S)\pi)$ spectrum
- Understanding details difficult
  - Resonances in $\psi(2S)\pi$ will contribute to $K\pi$ and its moments
  - Any fit to $\psi(2S)\pi$ on top of reflections neglects interference between two axes

Only K^* resonances

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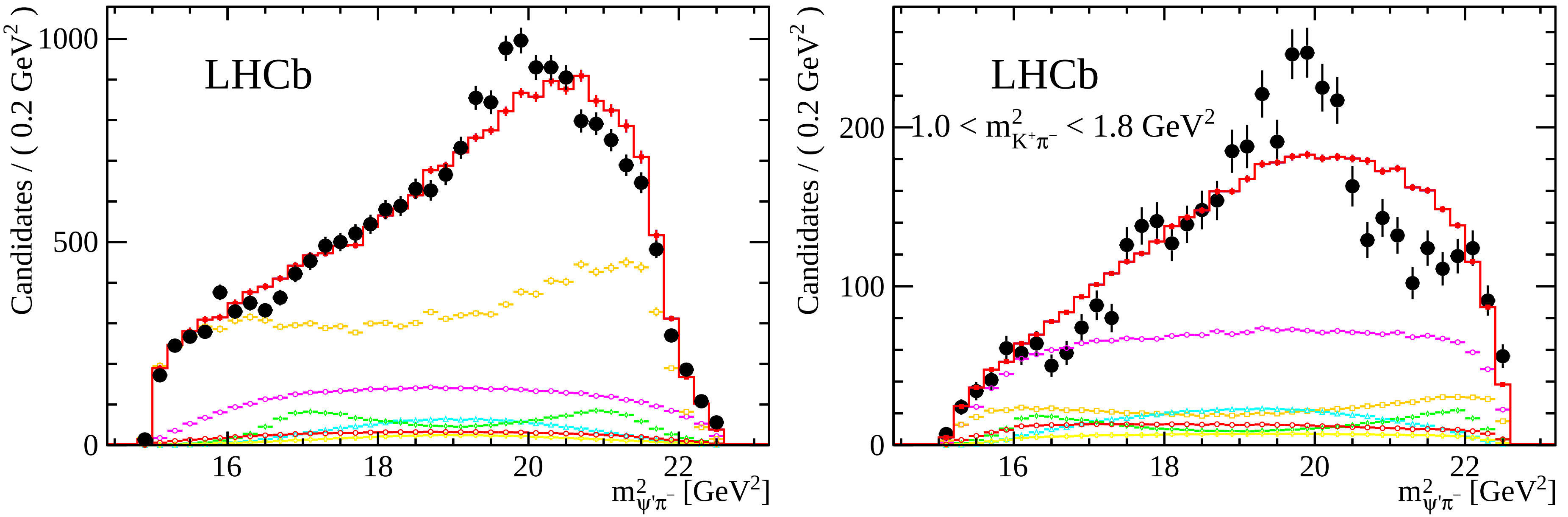
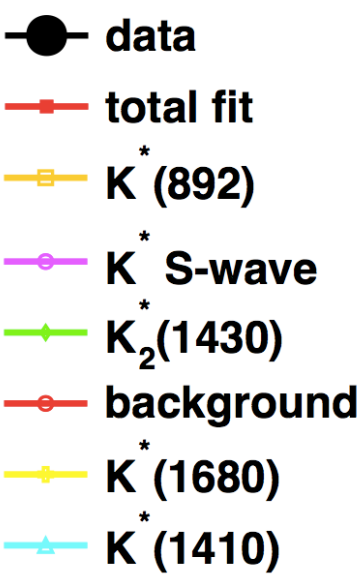
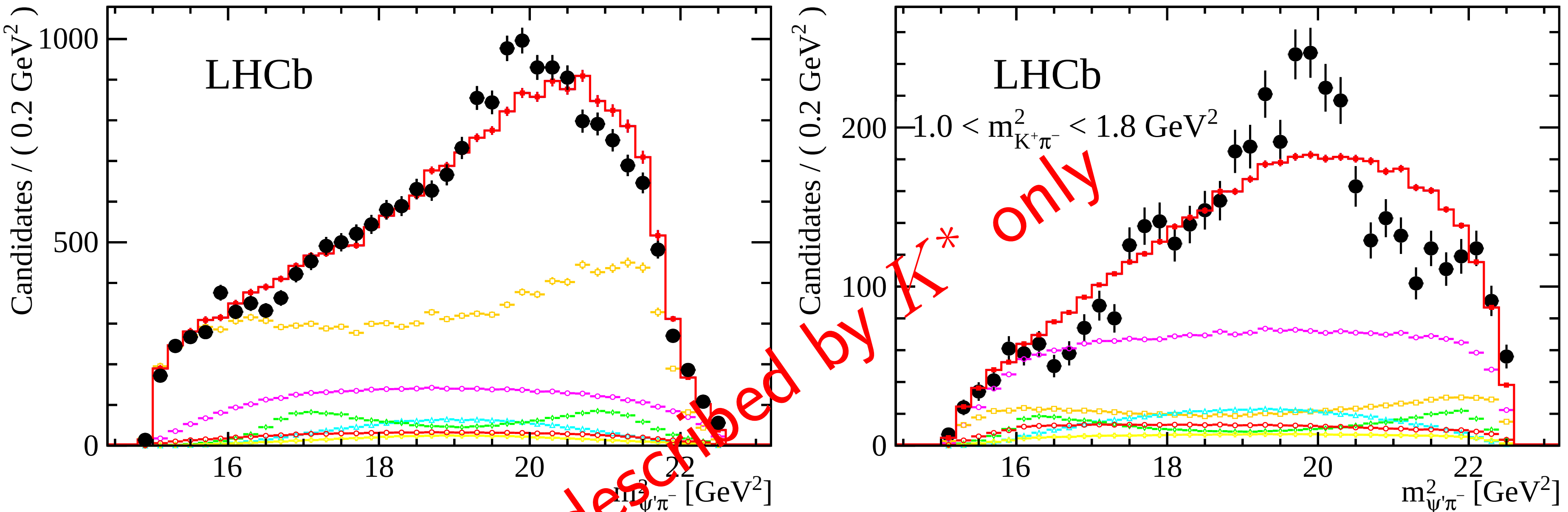


PRL 112 (2014) 222002

Resonance	J^P	Likely $n^{2S+1}L_J$	Mass (MeV)	Width (MeV)	$\mathcal{B}(K^{*0} \to K^+\pi^-)$
$K_0^*(800)^0$ (κ)	0^+	—	682 ± 29	547 ± 24	$\sim 100\%$
$K^*(892)^0$	1^-	1^3S_1	895.94 ± 0.26	48.7 ± 0.7	$\sim 100\%$
$K_0^*(1430)^0$	0^+	1^3P_0	1425 ± 50	270 ± 80	$(93 \pm 10)\%$
$K_1^*(1410)^0$	1^-	2^3S_1	1414 ± 15	232 ± 21	$(6.6 \pm 1.3)\%$
$K_2^*(1430)^0$	2^+	1^3P_2	1432.4 ± 1.3	109 ± 5	$(49.9 \pm 1.2)\%$
$B^0 \to \psi(2S)K^+\pi^-$ phase space limit			1593		
$K_1^*(1680)^0$	1^-	1^3D_1	1717 ± 27	322 ± 110	$(38.7 \pm 2.5)\%$
$K_3^*(1780)^0$	3^-	1^3D_3	1776 ± 7	159 ± 21	$(18.8 \pm 1.0)\%$
$K_0^*(1950)^0$	0^+	2^3P_0	1945 ± 22	201 ± 78	$(52 \pm 14)\%$
$K_4^*(2045)^0$	4^+	1^3F_4	2045 ± 9	198 ± 30	$(9.9 \pm 1.2)\%$
$B^0 \to J/\psi\, K^+\pi^-$ phase space limit			2183		
$K_5^*(2380)^0$	5^-	1^3G_5	2382 ± 9	178 ± 32	$(6.1 \pm 1.2)\%$



Only K^* resonances



Data cannot be described by K^* only

PRL 112 (2014) 222002

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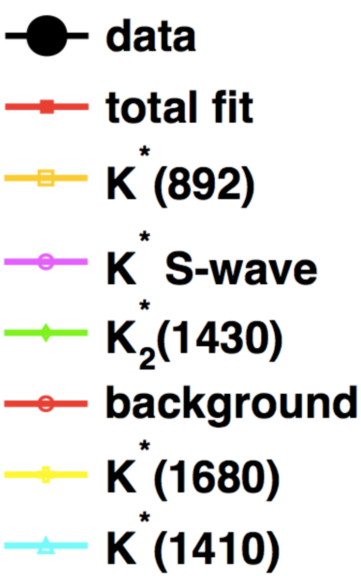
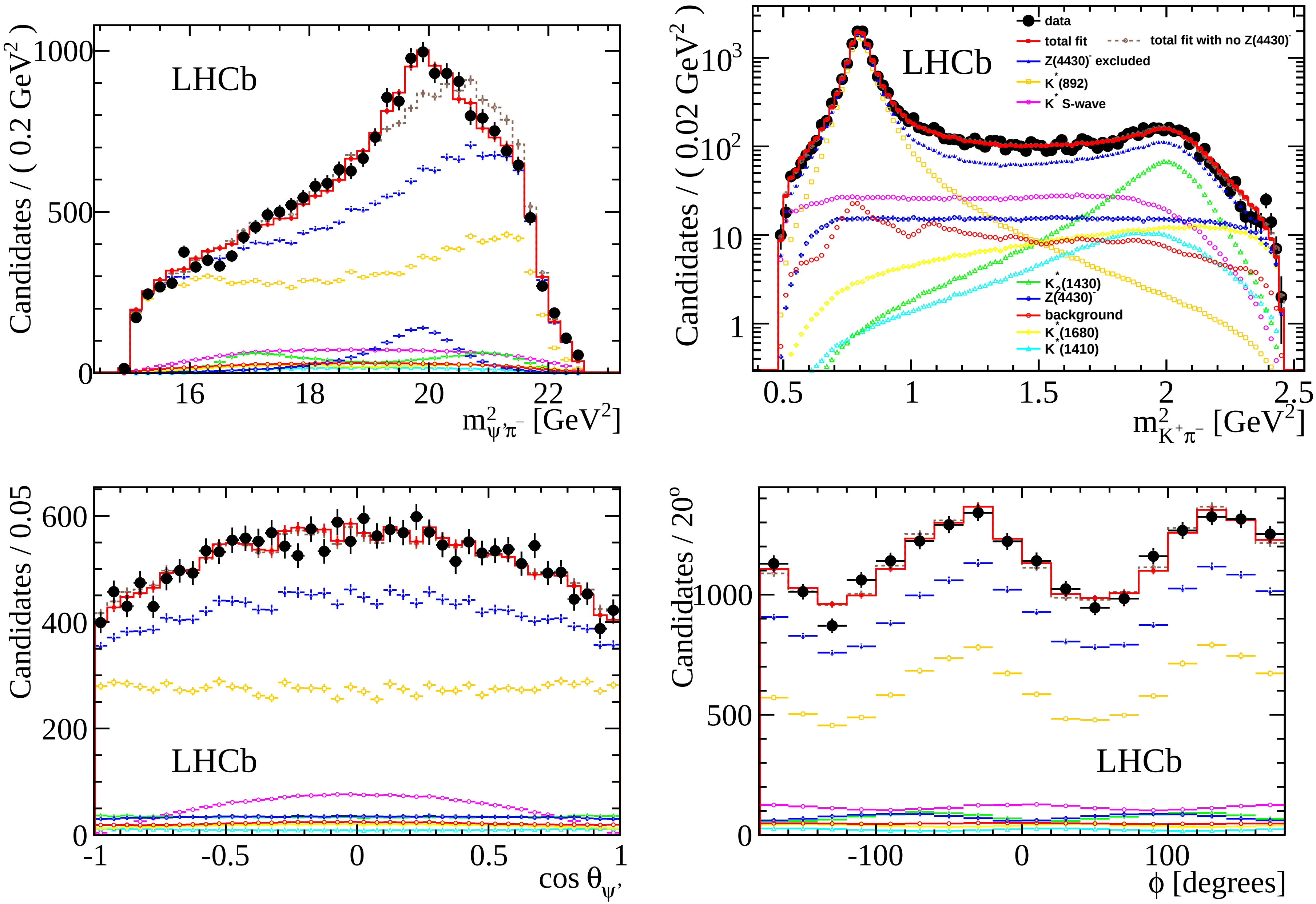


Adding Z$^+$



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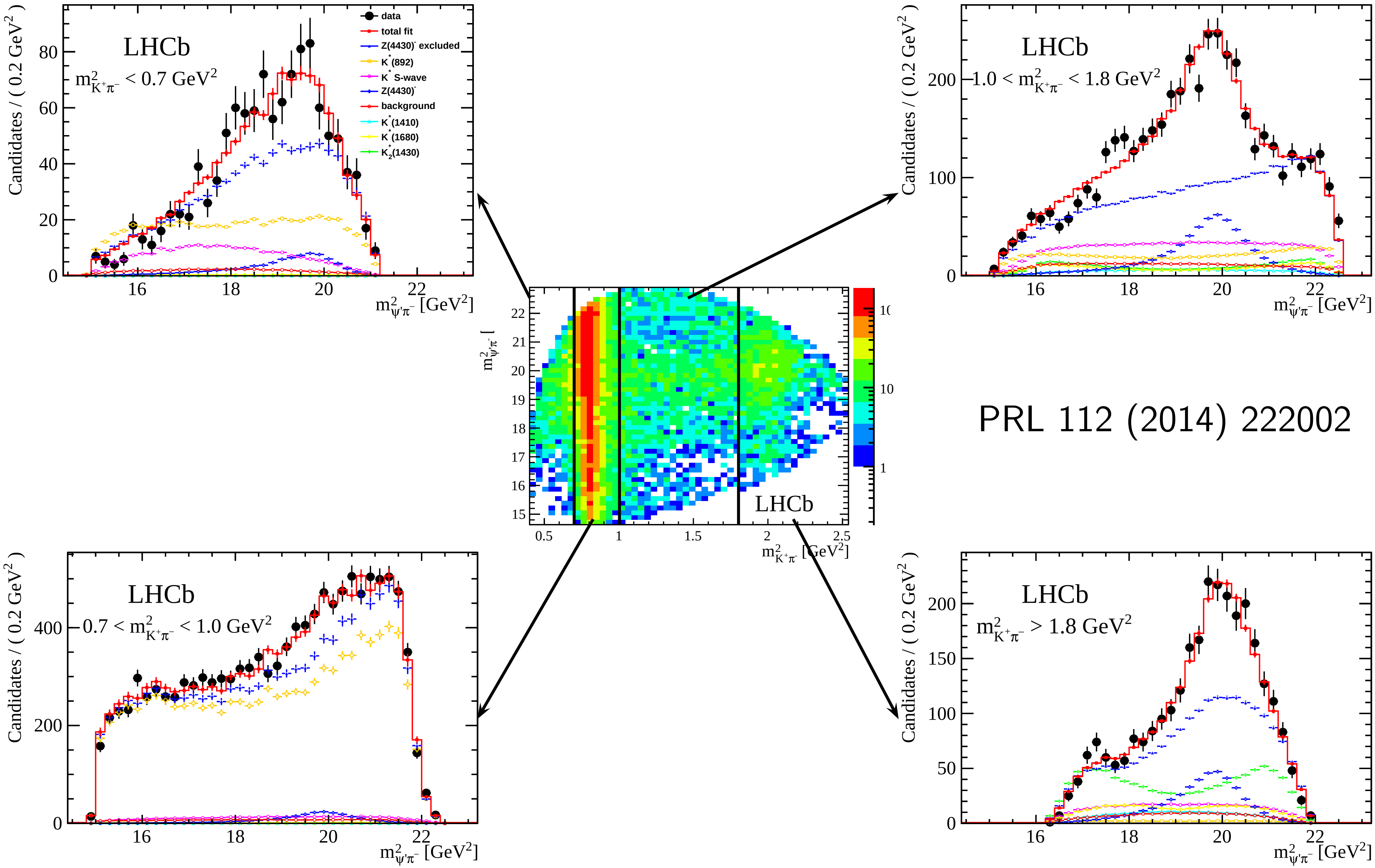
Dalitz plot slices



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Results

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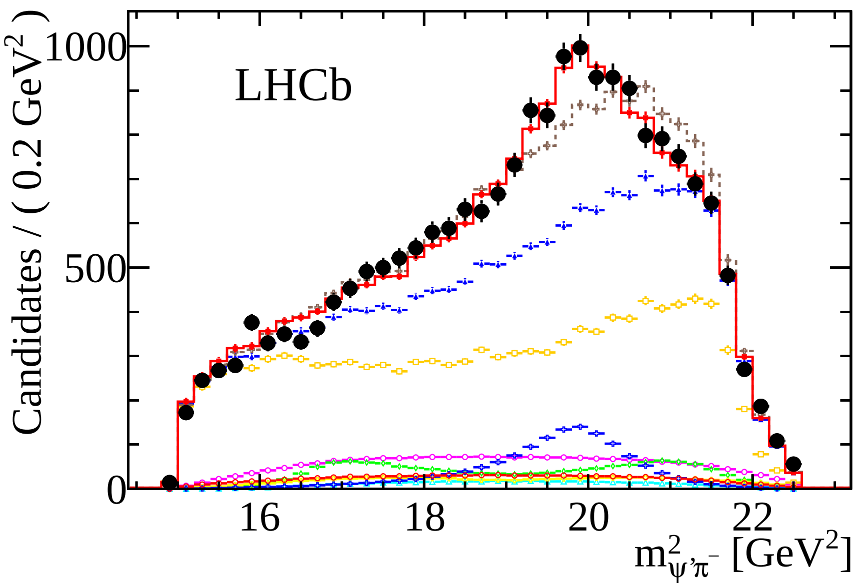

$M(Z)$	$4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma(Z)$	$172 \pm 13^{+37}_{-34}$ MeV
f_Z	$5.9 \pm 0.9^{+1.5}_{-3.3}$ %
f_Z^I	$16.7 \pm 1.6^{+2.6}_{-5.2}$ %
Significance	$> 13.9\sigma$

- Data are described well with 1^+ $Z(4430)^+$ contribution (χ^2 p-value 12%)
- Parameters extracted consistent with Belle
- Large interference effects seen
- Adding additional K^* resonances to model does not alter conclusion

$$f_Z = \frac{\int A_Z(\Omega)d\Omega}{\int A(\Omega)d\Omega} \qquad f_Z^I = 1 - \frac{\int A_{\mathrm{no}Z}(\Omega)d\Omega}{\int A(\Omega)d\Omega}$$

$Z(4430)^+$ spin

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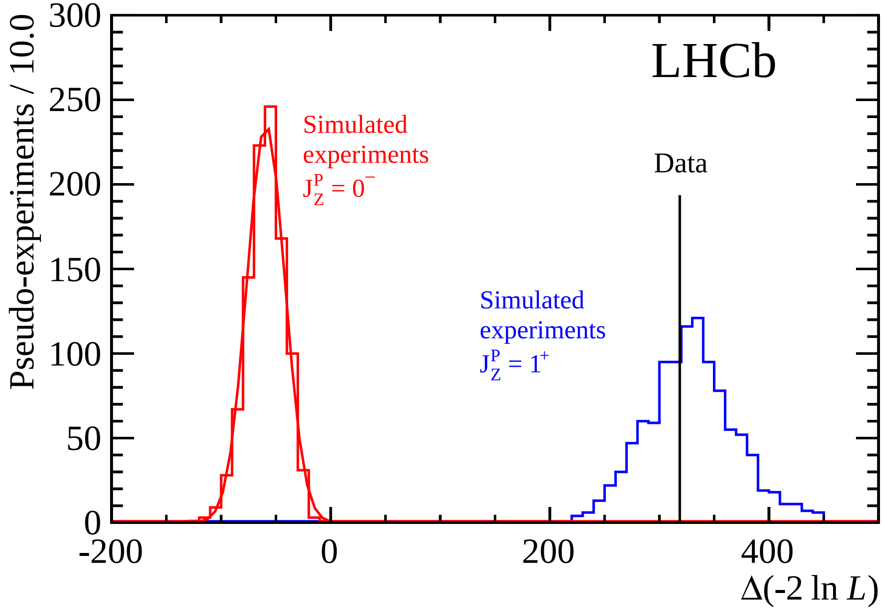

Hypothesis	Rejection
0^-	$9.7\,\sigma$
1^-	$15.8\,\sigma$
2^+	$16.1\,\sigma$
2^-	$14.6\,\sigma$

- As we use full kinematic information, we have sensitivity to quantum numbers
- Test spins 0,1 and 2 with both parities
- Based on likelihood ratio
- Quote exclusion based on asymptotic formula (lower bound)
- Verified by simulation
- All rejections relative to 1^+
- $Z(4430)^+$ is 1^+ state without any doubts

Is $\mathbf{Z(4430)^+}$ resonance?

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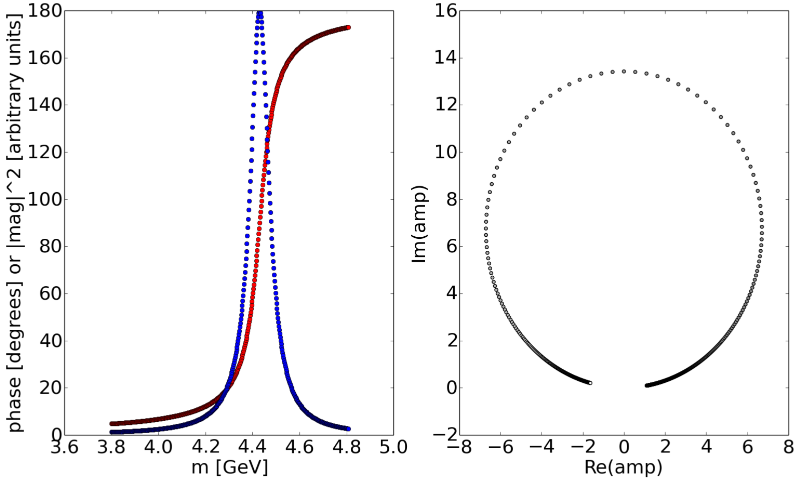

$$\frac{1}{m_R^2 - m^2 - i m_R \Gamma(m, \Gamma_R)}$$

- Data are consistent with BW for $Z(4430)^+$
- But will they follow if BW is not imposed?
- Change BW in $Z(4430)^+$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins
- Plot resulting amplitude on Argand plot

Is $Z(4430)^+$ resonance?

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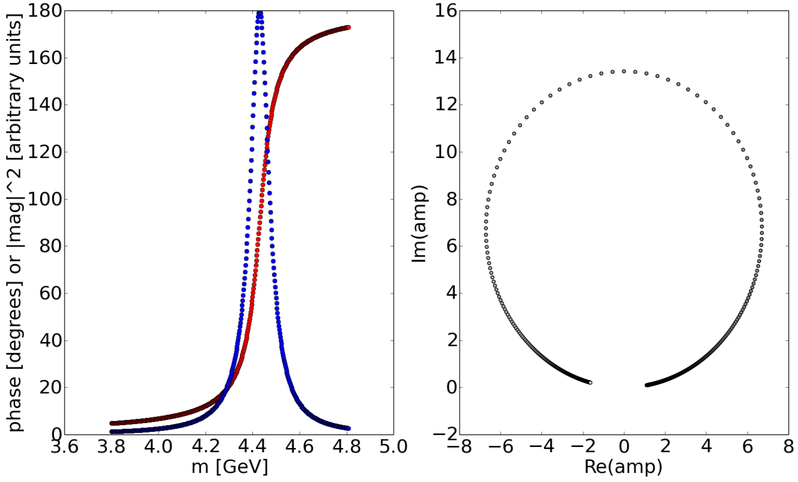

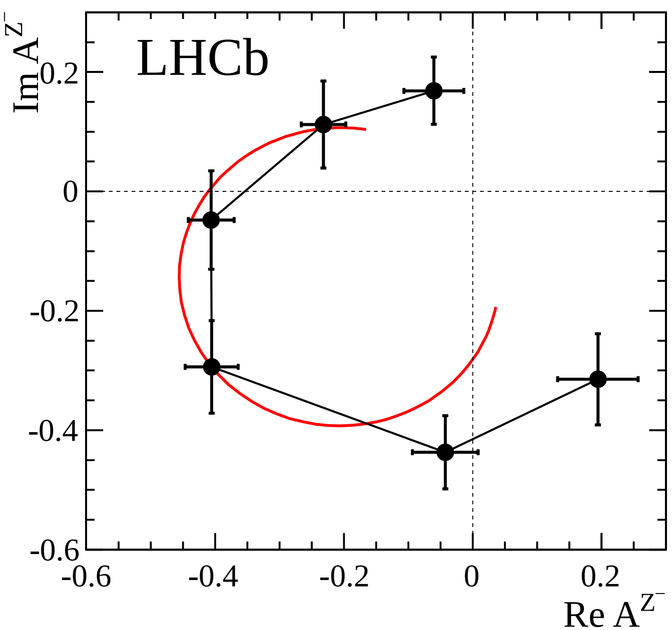

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$\Rightarrow$ It shows resonance behaviour without imposing it

Second Z^+ state

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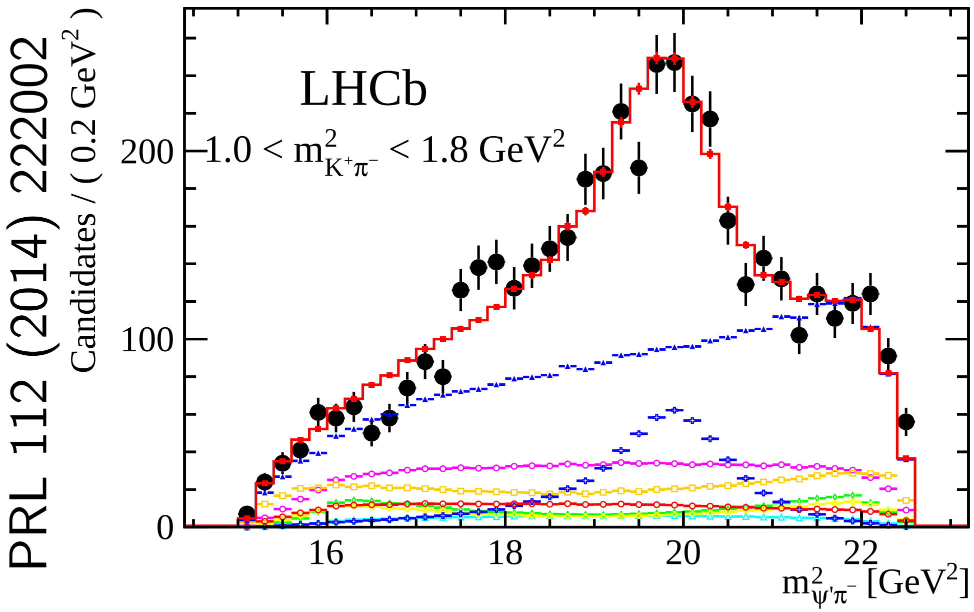

$M(Z_0)$	$4239 \pm 18^{+45}_{-10}$ MeV
$\Gamma(Z_0)$	$220 \pm 47^{+108}_{-74}$ MeV
f_{Z_0}	$1.6 \pm 0.5^{+1.9}_{-0.4}$ %
$f^I_{Z_0}$	$2.4 \pm 1.1^{+1.7}_{-0.2}$ %
Significance	6σ

- Data can be described even better by adding second $\psi(2S)\pi$ state
- On its own, it is significant
- Preferred 0^- (but 660 ± 150 MeV wide 1^+ option cannot be ruled out)

- Argand diagram is inconclusive
- No evidence in model-independent approach
- Will need more data to clarify situation

Second Z^+ state

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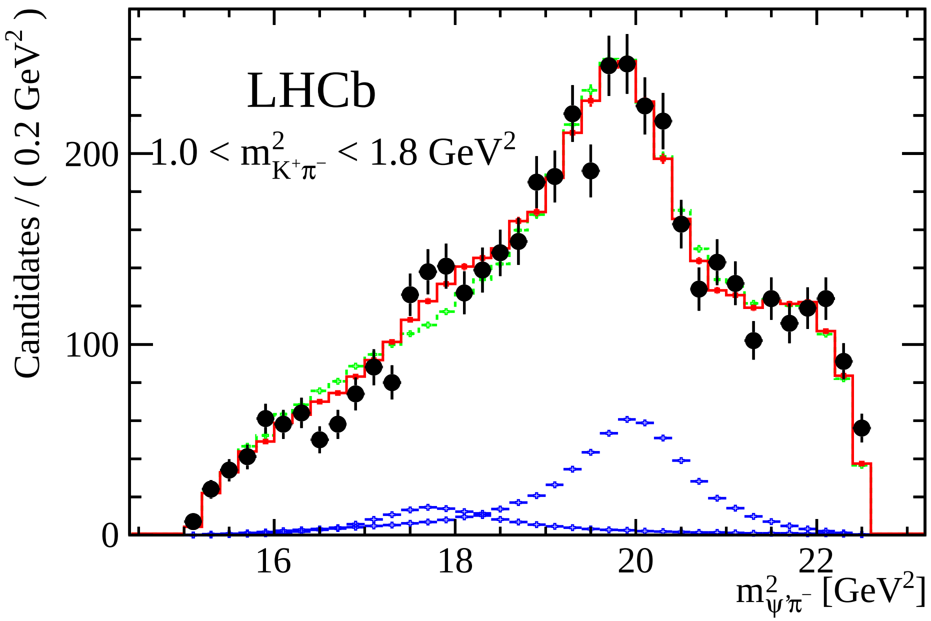

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Excitement?

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LHCb confirms existence of exotic hadrons

How CERN's Discovery of Exotic Particles May Affect Astrophysics

by BRIAN KOBERLEIN *on* APRIL 10, 2014

大型强子对撞机捕获到神秘粒子Z (4430)

或许成为物质形式“四夸克态”存在的有力证据

2014/04/13　15:46

LHCb実験を行っている国際研究チームが、4個のクォークが結合した粒子である「Z(4430)⁻」を合成したと発表した。Z(4430) としては、初発見から7年目にしてようやく別の研究チームが存在を立証した事になる。

นักฟิสิกส์ยืนยันพบฮาดรอนสองคว้ากสองแอนตีคว้าก

WRITTEN BY NATTY_SCI ON APRIL 13, 2014. POSTED IN ฟิสิกส์, วิทยาศาสตร์

ล่าสุด เครื่อง LHCb ได้มีการศึกษาอีกครั้งและใช้ข้อมูลอนุภาคจากเครื่องโดยตรงมาวิเคราะห์ แต่นำเอาเทคนิคการวิเคราะห์ของศูนย์ปฏิบัติการวิจัยเบลล์และ BaBar มาใช้ ศาสตราจารย์ชวาร์นิคกี้และทีมงานได้ยืนยันแล้วว่า Z(4430) นั้นมีอยู่จริง และ exotic hadron ก็มีอยู่จริงด้วย

Nowa forma materii: potwierdzono istnienie egzotycznych hadronów

13-04-2014 13:08 TO TRZECI RODZAJ HADRONÓW, DOTYCHCZAS WYRÓŻNIANO BARIONY I MEZONY

CONFIRMADA L'EXISTÈNCIA D'UNA NOVA PARTÍCULA SUBATÒMICA

"המובהקות לאותות של Z (4430) מדהימה – לפחות 13.9 סיגמה – דבר המאשר את קיומו של מצב זה" אמר דובר LHCb פיירולואיג'י קמפנה. "ניתוח ה- LHCb חשף את הטבע המהדהד של המבנים הנצפים, והוכיח כי זהו באמת חלקיק, ולא תכונה מיוחדת של הנתונים".

Эксперимент LHCb окончательно доказал реальность экзотического мезона Z(4430)

PISTOLA FUMANTE DI UNA PARTICELLA A QUATTRO QUARK

Objavili čudnú časticu, urýchľovač ju potvrdil

LHCb kinnitas tetrakvargi olemasolu

LHC Beauty Tangkap Z (4430) Mungkin Tetraquark

Mystisk partikel udfordrer fysikernes kvarkmodel

SPIEGEL ONLINE WISSENSCHAFT

Exotisches Teilchen: Physikern gelingt Nachweis eines Partikels aus vier Quarks

Các nhà nghiên cứu tại LHC xác nhận sự tồn tại của hạt Tetraquark: tổ hợp tạo thành từ 4 quark

Thảo luận trong 'Khoa học' bắt đầu bởi ndminhduc, 15/4/14.

De LHCb heeft 't bevestigd: er bestaan exotische hadronen

10 APRIL 2014 DOOR ARIE NOUWEN • REAGEER

تاکنون کشف ذره (4430)Z در سال 2007 بشدت جنجال برانگیز بود و فیزیکدانان بر سر موجودیت یا عدم موجودیت آن اختلاف نظر داشتند

تائید کنونی ذره با استفاده از آشکارساز LHCb ماورای هرگونه تردید منطقی موجود است.

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Παρασκευή, 11 Απριλίου 2014

Ο LHCb επιβεβαιώνει την ύπαρξη εξωτικού σωματιδίου, LHCb confirms existence of exotic hadrons

Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers 'Very Exotic Matter' That Challenges Traditional Physics! (Must-See Videos)

Thursday, April 17, 2014 19:57

SAT APR 12, 2014 AT 08:25 PM PDT

Tetra Quark: Not a New Star Trek Character, a New State of Matter.

Natuurkunde & wiskunde

CERN-fysici bevestigen bestaan nieuw exotisch deeltje

Interpretation

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- What $Z(4430)^+$ really is?
- Large decay width $\Rightarrow$ strong decay
- $c\bar{c}$ state in final state $\Rightarrow$ $c\bar{c}$ has to be also in initial state
- Charged, so cannot be conventional charmonia with $c\bar{c}$ only
- From Argand plot it behaves as resonance
- Often there are threshold effects (cusps) when new channels opens
    - In case of $Z(4430)^+$ we are close to $\overline{D}^*$–D_1 threshold
    - Cusp would be S-wave effect, so would have $J^P = 0^-$, 1^- or 2^-
    - We find $J^P = 1^+$ thus excluding threshold effect
- From all this all conventional explanations fail
- We have something "exotic" like tetraquark, molecule, ...
- If there is one "exotic" state, then there should be whole spectrum of them, so lot of work ahead of us
- First natural choice to look for is neutral partner of $Z(4430)^+$

Conclusions

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- At LHCb we collected large samples of B decays
- Started to check various claims for new states
  - Often those analyses are difficult as we want to do careful job
- We confirmed existence of $Z(4430)^+$
  - Belle and Babar had different conclusion due to lower statistics and lower sensitivity of method at Babar
- We improved measurement of $Z(4430)^+$ properties
- Our date show proper resonance behaviour of $Z(4430)^+$
- We exclude non-exotic interpretation of $Z(4430)^+$
- Exotic spectroscopy is now fully open for new states